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## EXTENSION OF A SIMPLIFIED COMPUTER PROGRAM FOR ANALYSIS OF SOLID-PROPELLANT ROCKET MOTORS

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Final Report



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16. ABSTRACT This report presents the results of research performed at Auburn University during the period from December 15, 1972, to April 15, 1972, under Modifications Nos. 8, 9 and 10 to the Cooperative Agreement, dated October 6, 1969, between the NASA Marshall Space Flight Center and Auburn University. The research is an extension of that accomplished under Modification No. 6 to the same agreement which culminated in the development of a simplified computer program for preliminary design and performance analysis of solid-propellant rocket motors (SRMs) as reported in Reference 1. The extension adds the following capabilities to the simplified program as program options. <ol style="list-style-type: none"> <li>1. Treatment of "wagon-wheel" cross-sectional propellant configurations alone or in combinations with circular perforated configurations.</li> <li>2. Calculation of ignition transients with the igniter treated as a small rocket motor.</li> <li>3. Accurate representation of spherical circular perforated grain ends as an alternative to the conical end surface approximation used in the original program.</li> <li>4. Graphical presentation of program results using the "CalComp 663" digital plotter.</li> </ol>					
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## ADDITIONAL NOMENCLATURE

See Reference 1 for the basic nomenclature. An asterisk before the symbol indicates an input variable. All input subscripted and non-subscripted variables are listed separately.

<u>English Symbol</u>	<u>Definition</u>	<u>Units Used</u>
$A_{GS1}, A_{GS2}, A_{GS}$	Cross-section area of a wagon-wheel grain associated with the first, second and both sets of grain points, respectively.	in <sup>2</sup>
$*C_{ig}$	Characteristic exhaust velocity of the igniter propellant	ft/sec
$*h_1, *h_2$	The half width of the first and second set of points, respectively, of a wagon-wheel grain	in.
$*I_{go}$	Integer designating option of ignition transient calculation.	_____
$*I_{po}$	Integer designating option of plotting results	_____
$*I_{wo}$	Integer designating option of inert weight calculations	_____
$*K_a, *K_b$	Empirical constants in the characteristic velocity versus chamber pressure linear relations (Eq. B4c) used for ignition transient calculations	ft/sec, ft/sec-psia
$*l_1, *l_2$	The length of the two parallel sides of the first and second set of points, respectively, of a wagon-wheel grain	in.
$*N(jj)$	Integer designating whether or not a specific output plot is desired	_____
$*P_{big}$	Value of chamber pressure $P_c$ at which a nozzle blowout plug in the main motor is ejected	psia

<u>English Symbol</u>	<u>Definition</u>	<u>Units Used</u>
$*P_{mig}$	Maximum chamber pressure attained in the igniter	psia
$R_3$	Distance from center of curvature of a spherical end of circular perforated grain to the burning surface associated with $\theta_G$	in.
$*R_{ig}$	Average regression rate of the first half of the igniter pressure-time trace	psia/sec
$S_{G1}, S_{G2}, S_G$	Perimeter of a wagon-wheel grain associated with the first, second and both sets of grain points, respectively.	in.
$*t_{I1}, *t_{I2}$	Time for the igniter, pressure to reach maximum value and to decay to 10 percent of its maximum value, respectively	sec.
$*U_{fs}$	Flame spreading speed during ignition	in/sec
$*V_{ciT}$	Initial volume of chamber gases associated with tabular input	in <sup>3</sup>
$x_o', y_o'$	Coordinates of tips of wagon-wheel grain	in.
$x_1', y_1'$	Coordinates of intersections of burning slant sides of wagon-wheel grain points with fillet arcs (origins at fillet centers)	in.
<u>Greek Symbol</u>		
$*\alpha_1, *\alpha_2$	The angle between the slant sides of a wagon-wheel grain point and the center line of the point for the first and second set of points, respectively	radians
$*\Delta t_{ig}$	Time increment for ignition transients	sec
$\theta_{fw}$	Angular location of fillet centers with respect to radial centerline of wagon-wheel grain points	radians
$\lambda$	Volumetric loading density; i.e., initial volume occupied by propellant divided by empty case volume	_____



<u>Greek</u> <u>Symbol</u>	<u>Definition</u>	<u>Units Used</u>
$\tau_{ww}$	Web thickness of wagon-wheel grain.	in.

Subscript

ig                    ignition

## I. INTRODUCTION AND SUMMARY

This report presents the results of research performed at Auburn University during the period from December 15, 1972, to April 15, 1972, under Modifications Nos. 8, 9 and 10 to the Cooperative Agreement, dated October 6, 1969, between the NASA Marshall Space Flight Center and Auburn University. The research is an extension of that accomplished under Modification No. 6 to the same agreement which culminated in the development of a simplified computer program for preliminary design and performance analysis of solid-propellant rocket motors (SRMs) as reported in Reference 1.

The extension adds the following capabilities to the simplified program as program options.

1. Treatment of "wagon-wheel" cross-sectional propellant configurations alone or in combinations with circular perforated configurations.
2. Calculation of ignition transients with the igniter treated as a small rocket motor.
3. Accurate representation of spherical circular perforated grain ends as an alternative to the conical end surface approximation used in the original program.
4. Graphical presentation of program results using the "CalComp 663" digital plotter.

In addition, inert weight calculations are made optional in the new program whereas they were required calculations in the original program necessitating specification of input values. Also, the initial and final gaseous chamber volumes are eliminated as input requirements in the new program. These values are now calculated from the other program inputs. Finally, the computer program has been modified in detail for the purpose of simplifying the program and minimizing the computation time. The net result of the extensions, however, is an increase in compilation time to a maximum of about 2 minutes and 20 seconds and an increase in execution time to about 20 seconds in the IBM 360 computer. Almost all of the increase is attributable to the ignition transient calculations. The new program uses approximately 19,000 words on the IBM 360.

The present report is prepared as an addendum to the original report. Familiarity of the reader with Reference 1 is assumed. Thus, the extensive

notation of the original report is not repeated; only the new notation is given. The new input variables or deletions are discussed in Section II. The organization of the entire report follows that of the original report and equations are numbered consecutively with respect to the original report to provide for insertion at the appropriate locations in the original analysis. Figures and tables are numbered similarly according to whether they replace or supplement those of the basic report.

Flowcharts of the two new subroutines (ignition and graphical representation) are presented in Section IV but no attempt has been made to modify the flowcharts of the main program because the logic of the modifications is a straightforward extension of that of the original program and is made clear from the mathematical analyses presented in Section III. The new data card format is shown in Table IV-1 and the complete extended program is listed in Table IV-2. Program statements that must be removed in order to delete the CalComp plotter compilation requirements are indicated by check marks (►) in Table IV-2. Removal of these statements is necessary if the computer is not equipped for "CalComp" plotting. However, if alternate plotters are available, generally only the plotting subroutine need be replaced.

Test cases are given in Section V to illustrate (1) ignition transient calculations, (2) spherical closure effects with circular perforated grains, (3) graphical representation of program result, and (4) computation for "wagon-wheel" cross-sectional grain configuration.

## II. DISCUSSION OF INPUT AND OUTPUT

In this section each new input variable is defined in the order in which it is encountered in the program. Deletions or other changes in original variables are similarly treated. As in Reference 1, appropriate additional discussion of the variable and typical numerical values are given. New output variables of the program are also identified and defined.

### Users Options

- |                      |  |  |
|----------------------|--|--|
| $I_{go}$ (IGO)       | 0  | For no ignition transient computations                         |
|                      | 1  | For ignition transient computations                            |
| $I_{wo}$ (IWO)       | 0  | For no inert weight computations                               |
|                      | 1  | For inert weight computations                                  |
| $I_{po}$ (IPO)       | 0  | For no plots   |
|                      | 1  | For plots of equilibrium burning only                          |
|                      | 2  | For plots of ignition transients only                          |
|                      | 3  | For plots of both ignition transients and equilibrium burning. |
| $N(jj)$ (NUMPLT(JJ)) | An integer designating whether or not a specific output plot is desired: |  |
|                      | 0  | If a specific plot is not desired                              |
|                      | 1  | If a specific plot is desired                                  |
|                      | The order of specification of NUMPLT(JJ) is as follows:                  |  |
|                      | 1  | PHEAD versus T   |
|                      | 2  | PONoz versus T   |
|                      | 3  | PHEAD and PONoz versus T (superimposed)                        |

- 4 RHEAD versus T
- 5 RNOZ versus T
- 6 RHEAD and RNOZ versus T (superimposed)
- 7 SUMAB versus T
- 8 SG versus T
- 9 SUMAB and SG versus T (superimposed)
- 10 F versus T
- 11 FVAC versus T
- 12 F and FVAC versus T (superimposed)
- 13 VC versus T
- 14 SUMAB versus Y
- 15 SG versus Y
- 16 SUMAB and SG versus Y (superimposed)

Primary Basic Motor Dimensions

$V_{ci}, V_{cf}$  (VCI, VCF) Initial and final volume of chamber gases, respectively. These are deleted as input variables in the new program except for volume associated with tabular input. See  $V_{ciT}$  below.

Ignition Characteristics. Not required if ignition calculations are not desired (IGO = 0)

$K_a, K_b$  (KA, KB) Empirical constants in the characteristic velocity versus chamber pressure relationship for the main motor (ft/sec, ft/sec-psia). A linear relationship is assumed. Data are obtained from thermochemical calculations.

$U_{fs}$  (UFS) Flame spreading speed (in/sec). Reference 2 cites a value of 3650 in/sec for one composite type propellant with ammonium perchlorate oxidizer and aluminum additives. Values will differ for various specific propellants.

$C_{ig}^*$ (CSIG)	Characteristic velocity of the igniter propellant (ft/sec).
$P_{mig}$ (PMIG)	Maximum chamber pressure of igniter when discharging into the atmosphere (psia). This pressure is usually established based upon minimization of the igniter weight. It will ordinarily range from 80 to 150 percent of the maximum operating pressure of the main motor.
$t_{I1}$ (TI1)	Time for the igniter pressure to reach its maximum pressure (sec). Values range from 0.010 sec for a small igniter to 0.050 sec for a large igniter.
$t_{I2}$ (TI2)	Time for the igniter pressure to decay to 10 percent of its maximum value when discharging into the atmosphere (psia/sec). Typical values range from 0.2 to 0.5 seconds in smaller igniters to 0.5 to 1.2 in very large igniters.
$R_{ig}$ (RRIG)	Average regression rate of the first half of the igniter pressure time trace (psia/sec). Most igniter traces are generally regressive or two-level with the higher level occurring first. The analysis considers only the first half of the pressure time trace, because the contribution of the mass flow rate of the igniter to total mass flow rate is insignificant beyond this region during a normal ignition.
$\Delta t_{ig}$ (DELTIG)	Time increment for calculation of ignition transients (sec). A value of 0.001 seconds is recommended for small motors and 0.005 seconds for very large motors.
$P_{big}$ (PBIG)	Value of chamber pressure $P_c$ at which a nozzle blowout plug in the main motor is ejected (psia). If no blowout plug is used, PBIG should be set equal to an estimate of the atmospheric pressure when ignition is initiated.

#### Basic Properties of Weight Calculations

These inputs as listed in the original program are no longer required if calculation of inert weight is not desired (IWO = 0)

Input to Establish the Program and Basic Grain Configuration and Arrangement

$S_{op}$  (STAR)                      Add: 3 for wagon-wheel (See Figure II-4)

$C_{op}$  (COP)                      For extreme ends of a circular perforated grain only:

- 0    If both ends are conical or flat.
- 1    If head end is conical or flat and aft end is spherical.
- 2    If both ends are spherical.
- 3    If head end is spherical and aft end is conical or flat.

If the end of a circular perforated grain is taken spherical, the corresponding angle THETACH or THETACH is not used in the program.

Tabular Burning Surface and Port Areas (Not required for INPUT=2)

$V_{ciT}$                       Initial volume of chamber gases associated with tabular input (in<sup>3</sup>)

Basic Geometry for Star Grains

In order to simplify the conversion from the original to the extended program, the wagon-wheel is considered a type of star grain and each variable in this group as listed in the original program must be specified for wagon-wheel as well as standard star or truncated star grains.

Special Geometry for Wagon-Wheel Grain (Not required for standard or truncated star grains (STAR = 1 or 2))

$\tau_{ww}$                       The web thickness of wagon-wheel grain (in.). The discussion under TAUWS for standard star grains is applicable.

$l_1, l_2$  (L1, L2)                      The lengths of the pairs of parallel sides of the first and second set of grain points, respectively (in.) (See Figure II-4).

$\alpha_1, \alpha_2$   
(ALPHA1, ALPHA2)                      The angles between the slant sides and the center lines of the points of the first and second set of grain points, respectively (radians). The angles should not exceed  $\pi/2$  radians.

$h_w$  (HW)                      The half-width of the star points (in.). HW must not exceed TAUWW (HW  $\leq$  TAUWW).

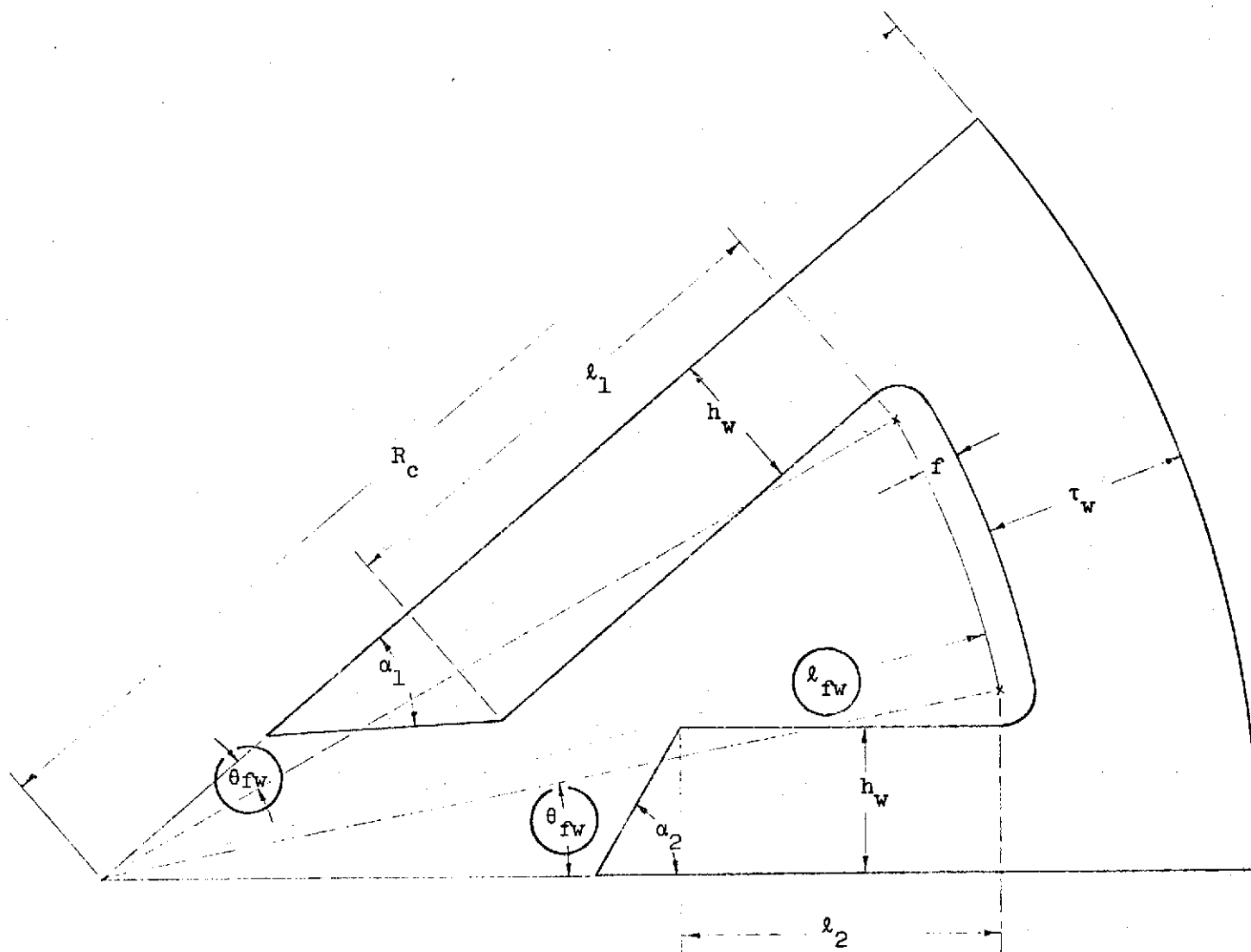


Figure II-4. Wagon-wheel grain cross-section. Calculated variables are circled.



### Additional Program Outputs

The outputs listed below are in addition to those of the original program. However, those outputs related to the ignition transient calculations are only obtained when  $IGO = 1$ . It should be noted that values of pressure (PONOZ and PHEAD) are based upon the assumption of choked flow through the nozzle and values of delivered thrust (F) and related values (e.g., CF) are based upon the additional assumption of the nozzle flowing full (no separation). This introduces errors in the output parameters mentioned during the initial phase of the ignition.

### Outputs as Functions of Time

$t_{ig}$ (TIG)	Operating time during ignition (sec.). This is calculated from the time of initiation of flame spreading.
$P_{c(ig)}$ (PCIG)	Chamber pressure within the igniter (psia). This is based on a piecewise linear pressure versus time relation before and after peak igniter pressure is encountered until the main motor pressure feeds back and controls the igniter pressure.

### Non-Time Varying Quantities

$A^*_{ig}$ (ASIG)	Required igniter throat cross-sectional area (in <sup>2</sup> ).
$\dot{m}_{ig(av)}$ (MIGAV)	Average mass flow rate of the igniter discharge over the first half of the igniter burning time excluding time prior to T11 (slugs/sec).
$W_{ig(tot)}$ (WIGTOT)	Estimated total weight of required igniter propellant (lbs.). This is based on the integral of $\dot{m}_{ig}$ over the time interval from T11 to T12/2 plus a somewhat arbitrary allowance of two-thirds the stated integral to provide sustained heat transfer feedback during the final ignition phase and propellant for the pressure buildup phase within the igniter (see Eq. B9).
$V_{ci}, V_{cf}$ (VCI, VCF)	Initial and final volume of chamber gases, respectively (in <sup>3</sup> )
$\lambda$ (LAMBDA)	Volumetric loading density; i.e., initial volume occupied by the propellant divided by the empty case volume (1). Note discussion after Eq. 37d.

### III. ANALYSIS

In this section the extensions to the mathematical analysis of the SRM design problem are presented in a step by step procedure following the method of the original report (Reference 1). The steps in the procedure are numbered consecutively with respect to those steps of the original report to permit insertion at the appropriate locations in the original analysis. In the few instances where one of the original analysis steps has been revised, the new analysis step bears the same number as the original step.

#### Burning Surfaces and Port Areas

##### End Geometry of Circular Perforated Grains

A0.h. Select an option for the circular perforated grain end configuration.

If both ends are conical or flat, set  $C_{op} = 0$ .

If head end is conical or flat and aft end spherical, set  $C_{op} = 1$ .

If head and aft ends are both spherical, set  $C_{op} = 2$ .

If head end is hemispherical and aft end conical or flat,  $C_{op} = 3$ .

A4.b. (revised) For the perforations.

If  $2y + D_i > D_o$ , set  $A_{unc} = A_{bpc} = 0$ ,

Go to step A5

If not and if  $\theta_G \leq 5^\circ$  and

if  $C_{op} = 0$ , compute

$$L_{Gc} = L_{Gci} - y (\cot \theta_{cn} + \theta_{ch})$$

if  $C_{op} = 1$  compute

$$L_{Gc} = L_{Gci} - \{ [D_o^2 - (D_i + \Delta D_i)^2]^{\frac{1}{2}} - [D_o^2 - (D_i + \Delta D_i + 2y)^2]^{\frac{1}{2}} \} / 2 - y \cot \theta_{ch}$$

if  $C_{op} = 2$ , compute

$$L_{GC} = L_{Gci} - \{ [D_o^2 - D_i^2]^{\frac{1}{2}} - [D_o^2 - (D_i + 2y)^2]^{\frac{1}{2}} \}$$

if  $C_{op} = 3$ , compute

$$L_{Gc} = L_{Gci} - \{[D_o^2 - D_i^2]^{1/2} - [D_o^2 - (D_i + 2y)^2]^{1/2}\}/2 - y \cot \theta_{cn}$$

$$A_{bpc} = \pi(D_i + 2y)[L_{Gc} - T_\ell = S] \quad \text{for } A_{bpc} > 0$$

$$A_{bpc} = 0 \text{ for } A_{bpc} \leq 0, \text{ or}$$

If  $\theta_G > 5^\circ$  and

if  $C_{op} = 0$  or 1, compute

$$A_{bpc} = \pi(D_i + 2y)\{L_{Gci} - y \cot \theta_{ch} - T_\ell - [S + \tan(\theta_G/2)]y\} \quad \text{for } A_{bpc} > 0$$

if  $C_{op} = 2$  or 3, compute

$$A_{bpc} = \pi(D_i + 2y)\{L_{Gci} - \{[D_o^2 - D_i^2]^{1/2} - [D_o^2 - (D_i + 2y)^2]^{1/2}\}/2 - T_\ell - [S + \tan(\theta_G/2)]y\} \quad \text{for } A_{bpc} > 0$$

$$A_{bpc} = 0 \text{ for } A_{bpc} \leq 0.$$

A4.c. (revised) For the nozzle end surface.

If  $\theta_G \leq 5^\circ$ , set  $A_{bnc} = 0$

If  $\theta_G > 5^\circ$  and  $C_{op} = 1$  or 2

$$R_3 = [(D_i + \Delta D_i)/2 + L_{Gni} \sin \theta_G] \cos \theta_G - (\sin \theta_G) \{[(D_o/2)^2 - [(D_i + \Delta D_i)/2 + L_{Gni} \sin \theta_G]^2]^{1/2} \text{ and}$$

$$A_{bnc} = \pi [L_{Gni} - R_3 - y \tan (\theta_G/2)] \{ (Di + \Delta Di)/2 \\ + y + (\sin \theta_G) [(D_o/2)^2 - (R_3 + y)^2]^{1/2} \\ + (R_3 + y) \cos \theta_G \} \quad \text{for } A_{bnc} > 0$$

$$A_{bnc} = 0 \text{ for } A_{bnc} < 0$$

If  $\theta_G > 5^\circ$  and  $C_{op} = 0$  or  $3$

$$A_{bnc} = \pi [L_{Gni} - y \cot (\theta_G + \theta_{cn}) - y \tan (\theta_G/2)] [Di + \Delta Di \\ + y + L_{Gni} \sin \theta_G + y \csc (\theta_G + \theta_{cn}) \sin \theta_{cn}] \quad \text{for } A_{bnc} > 0$$

$$A_{bnc} = 0 \text{ for } A_{bnc} \leq 0$$

Note: For  $\theta_G > 5^\circ$ , the entire burning end surface is treated as conical although a non-conical surface area evolves when

$\theta_G + \theta_{cn} > \pi/2$  for  $C_{op} = 0$  or  $3$  or when an analogous situation exists for  $C_{op} = 1$  or  $2$ .

#### Wagon-Wheel Cross-Sectional Geometry

A7.c. If  $G_{op} = 2$  or  $3$  and  $S_{op} = 3$

Go to step A17a

A17.a. Compute the radius of the fillet centers for a wagon-wheel grain.

$$l_{fw} = R_c - r_{ww} - f$$

b. Compute the angular location of the fillet centers

$$\theta_{fw} = \arcsin [(h_w + f)/l_{fw}]$$

A.18. Compute the grain perimeters  $S_{G1}$  and  $S_{G2}$  and initial cross-sectional areas  $A_{GS1}$  and  $A_{GS2}$  using  $l = l_1$  and  $\alpha = \alpha_1$  and then  $l = l_2$  and  $\alpha = \alpha_2$  in the following equations.

A18.a. If  $y + f \leq l_{fw} \sin \theta_{fw}$  and  $y \tan (\alpha/2) \leq l$ ,

$$S_G = n_p [l - 2y \tan (\alpha/2) + (l_{fw} \sin \theta_{fw} - f)/\sin \alpha - y \cot \alpha \\ + (f+y)(\pi/2 + \theta_{fw}) + (l_{fw} + f + y)(\pi/n_p - \theta_{fw})]$$

Go to step 18c

If  $y + f > l_{fw} \sin \theta_{fw}$ ,  $y \tan (\alpha/2) \leq l$  and

if  $y \leq \tau_{ww}$

$$S_G = n_p \{ (y+f)[\pi/n_p + \arcsin (\frac{l_{fw}}{y+f} \sin \theta_{fw})] \\ + l_{fw} (\pi/n_p - \theta_{fw}) \}$$

Go to step 18c

or if  $y > \tau_{ww}$

$$S_G = n_p (y+f) \{ \theta_{fw} + \arcsin (\frac{l_{fw}}{f+y} \sin \theta_{fw}) \\ - \arcsin \left[ \frac{R_c^2 - l_{fw}^2 - (y+f)^2}{2l_{fw}(y+f)} \right] \} \text{ for } S_G > 0$$

$S_G = 0$  for  $S_G \leq 0$

Go to step 18c

A18.b. If  $y \tan (\alpha/2) > l$  compute the coordinates,  $x_1'$  and  $y_1'$ ,

(origin at fillet center) of intersections of burning slant sides with fillet arcs:

If  $\alpha \geq \pi/2$ ,

$$x_1' = -l + y \text{ and}$$

$$y_1' = -[(f+y)^2 - x_1'^2]^{1/2}$$

If  $\alpha < \pi/2$

$$Q \equiv -f + l \tan \alpha - y/\cos \alpha$$

$$x_1' = -Q \tan \alpha - [-Q^2 + (f+y)^2 \sec^2 \alpha]^{1/2} / \sec^2 \alpha$$

$$y_1' = x_1' \tan \alpha + Q$$

and the coordinates of the tips of grain points,

$$y_o' = -l_{fw} \sin \theta_{fw} \text{ and}$$

$$x_o' = -l + y \quad \text{for } \alpha \geq \pi/2 \text{ or}$$

$$x_o' = (y_o' - Q)/\tan \alpha \quad \text{for } \alpha < \pi/2$$

Then compute burning perimeters:

If  $y + f \leq [(l_{fw} \sin \theta_{fw})^2 + x_1'^2]^{\frac{1}{2}}$  and

if  $y < \tau_{ww}$ ,

$$\begin{aligned} S_G = n_p \{ & [(x_1' - x_o')^2 + (y_1' - y_o')^2]^{\frac{1}{2}} \\ & + (f+y) [\pi/2 + \theta_{fw} - \arcsin (\frac{x_1'}{f+y})] \\ & + (l_{fw} + f+y)(\pi/n_p - \theta_{fw}) \} \end{aligned} \quad \text{Go to step 18c}$$

or if  $y \geq \tau_{ww}$ ,

$$\begin{aligned} S_G = n_p \{ & [(x_1' - x_o')^2 + (y_1' - y_o')^2]^{\frac{1}{2}} \\ & + (f+y) [\pi/2 - \arcsin (\frac{x_1'}{f+y})] \\ & - \arcsin \cos \left( \frac{R_c^2 - l_{fw} - (y+f)^2}{2l_{fw}(y+f)} \right) \} \text{ for } S_G > 0 \end{aligned}$$

$$S_G = 0 \quad \text{for } S_G \leq 0 \quad \text{Go to step 18c}$$

If  $y+f > [(l_{fw} \sin \theta_{fw})^2 + x_1'^2]^{\frac{1}{2}}$  and

if  $y \leq \tau_{ww}$ ,

$$\begin{aligned} S_G = n_p \{ & (y+f) [\pi/n_p + \arcsin (\frac{l_{fw}}{y+f} \sin \theta_{fw})] \\ & + l_{fw}(\pi/n_p - \theta_{fw}) \} \end{aligned} \quad \text{Go to step 18c}$$

or if  $y > r_{ww}$ ,

$$S_G = n_p (y+f) \left\{ \theta_{fw} + \arcsin \left( \frac{l_{fw}}{y+f} \sin \theta_{fw} \right) - \arcsin \left[ \frac{R_c^2 - l_{fw}^2 - (y+f)^2}{2l_{fw}(y+f)} \right] \right\} \text{ for } S_G > 0$$

$$S_G = 0 \text{ for } S_G \leq 0$$

A18.c. If  $y \leq 0$ , compute the (initial) cross-sectional area of the grain

$$A_{Gs} = (1/2) \{ \pi R_c^2 - n_p l_{fw}^2 \sin \theta_{fw} [\cos \theta_{fw} - (\sin \theta_{fw})(\cot \alpha) - 2(l+f \tan(\alpha/2))/l_{fw}] - (\pi - \theta_{fw} n_p) l_{fw}^2 - 2n_p f [l + l_{fw} \sin \theta_{fw}]/\sin \alpha + l_{fw}(\pi/n_p - \theta_{fw}) + (\pi/n_p + \pi/2 - \csc \alpha) f/2 \}$$

A19.a.  $S_G = S_{G1} + S_{G2}$

A19.b.  $A_{Gs} = A_{G1} + A_{G2}$

Go to step A24

#### Initial Chamber Volumes

A37.a. If  $y > 0$

Go to step 50

A37.b. If  $G_{op} = 1$ , set  $L_{Gsi} = 0$  and  $A_{Gs} = 0$

37.c. If  $G_{op} = 2$ , set  $L_{Gci} = 0$  and  $L_{Gni} = 0$

37.d. Compute the approximate initial gaseous volume of the chamber,

$$V_{ci} \approx 1.10 \{ \pi D_i^2 (L_{Gni} + L_{Gci})/4 + (\pi D_o^2/4 - A_{Gs}) L_{Gsi} + n_T l_{Tp} \pi D_{Tp}^2/4 \} + V_{ciT}$$

Go to step 50

Note: The volume is approximate because an approximate relation is used for the volume of the thrust chamber passages and because an arbitrary ten percent additional allowance is made to account for slot volume, end volume and the effect of the convergent portion of the nozzle on the chamber pressure change characteristics. Any error thus introduced in the final volume and the volumetric loading density will be roughly one order of magnitude less than the error in initial volume.

### Ignition Transients

This analysis is treated in the computer program as a major sub-routine. The method used follows the general technique described by Sforzini and Fellows (Reference 2) for an igniter which is itself a small rocket motor. Features of the analysis include variation of the characteristic velocity of the main motor with chamber pressure. Chamber volume and surface area of the propellant grain are assumed constant during ignition, but the burning surface is established as a function of time in accord with the passage of the flame front which is assumed to spread at constant speed. Four changes are made in the referenced approach:

1. A simple piecewise linear approximation to the pressure-time trace of the igniter (assumed to be a small SRM) is used rather than the polynomial approximation used in the reference. Comparison shows there is very little difference between computations by the two methods, and the program input is greatly simplified.
  2. The referenced analysis was modified to permit effects of erosive burning to be taken into account. This was accomplished by replacing the burning rate term  $C_p c^n$  in equation 9 of Reference 2 with the average burning rate as calculated by the methods used in the basic program of Reference 1.
  3. The igniter throat cross-sectional area is eliminated as an input variable by making use of an empirical criterion taken from Reference 3 for establishing the discharge mass flow rate of the igniter.
  4. Provision is made for including, as a program option, calculations accounting for the effects of a main motor nozzle blowout plug.
- B0. Set  $t_{ig} = 0$
- B1.a. Compute the average mass flow rate of the igniter over the first half of the igniter burning time, excluding the pressure buildup phase (Time prior to  $t_{I1}$ )

$$\dot{m}_{ig(av)} = 0.2A^*/g$$

This is an empirical relationship based upon Reference 3.

- B1.b. Calculate the required igniter throat cross-sectional area

$$A^*_{ig} = 2 \dot{m}_{ig(av)} C^*_{ig} / [2 P_{mig} - R_{rig} (t_{I2} - t_{I1}) / 2]$$



B2. Compute the chamber pressure of the igniter

B2.a. If  $t_{ig} \leq t_{I1}$ ,

$$P_{cig} = P_{mig} t/t_{I1}$$

B2.b. If  $t_{ig} > t_{I1}$  and  $P_{cig} > P_c$

$$P_{cig} = P_{mig} - R_{rig} (t - t_{I1})$$

B2.c. If  $t_{ig} > t_{I1}$  and  $P_{cig} \leq P_c$

$$P_{cig} = P_c$$

B3. Compute the estimated instantaneous mass flow rate of the igniter

If  $P_{cig} > P_c$

$$\dot{m}_{ig} = P_{cig} A^*_{ig}/C^*_{ig}$$

If  $P_{cig} \leq P_c$  or  $t_{ig} > t_{I2}/2$

$$\dot{m}_{ig} = 0 \text{ (See discussion after RRIG, Section II)}$$

B4. Solve the following equations for the chamber pressure of the main motor  $P_c$  using a Runge-Kutta solution of the fourth order

B4.a. If  $P_c < P_{big}$ , set  $\dot{m}_D = 0$

If  $P_c \geq P_{big}$ , set

$$\dot{m}_D = A^*P_c/(K_a + K_b P_c)$$

B4.b.  $r_h = a [P_c(1 + r^2 J^2/2)]^n$

B4.c.  $C^* = K_a + K_b P_c$

B4.d.  $r_n = a [P_c(1 - r^2 J^2/2)]^n$

$$+ \alpha_{eb} (P_c A^* X / C^* A_{pn})^{0.8} (u_{fs} t_{ig})^{0.2} \exp (\beta r_{np} A_{pn} C^* / P_c A^* X)$$

B5. Compute

$$P_h = P_c [1 + r^2 J^2 / 2]$$

B6. Set  $P_{on} = P_c$

B7. Calculate  $C_F$ ,  $C_{F \text{ vac}}$ ,  $F$ ,  $F_{\text{vac}}$ ,  $I_{sp \text{ vac}}$ ,  $I_T$ ,  $I_{T \text{ vac}}$  using equations 20 through 24 with  $t_j = t_{ig}$ .

B8. Set  $T_{ig} = \sum_k \Delta t_{ig \ k}$  Repeat step B2 through B7

for  $k = 1, 2, 3, \dots$

until  $P_{c(k)} - P_{c(k-1)} < P_{c(k)} / 1000$

B9. Calculate the estimated igniter propellant weight

$$W_{ig(tot)} = \dot{m}_{ig(av)} [5(t_{12} - t_{11}) / 6]$$

#### IV. THE COMPUTER PROGRAM

This section contains the instructions for preparation and arrangement of the data cards for the extended program. A complete listing of the program statements is given followed by flow charts for the two new sub-routines; the ignition and the plotting subroutine for the "CalComp 663" digital plotter.

##### Data Card Usage

The data formats have been established to allow the operator to look at the card and know which variables are represented on it. The format should be followed to insure correct reading of the inputs. The various data cards are as follows: (See Table IV-1 for the complete format)

- I. Number of configurations
- II. Initial zero values
- III a&b. User options (2 cards)
- IV. Propellant data
- V a&b. Motor geometry (2 cards)
- VI a&b. Performance data (2 cards)
- VII. Input, grain, etc.
- VIII a&b. Initial tabular inputs (2 cards)
- IX a&b. Tubular grain input (2 cards)
- X. General star data
- XI. Wagon wheel data
- XII. Truncated star data
- XIII. Standard star data
- XIV. Termination port data
- XV a&b. Data for ignition transient calculations (2 cards)
- XVI a-e. Data for weight calculations (5 cards)
- XVII a&b. Tabular inputs (2 cards)

NOTE: In the original report, tabular inputs and initial tabular inputs appeared under the same heading.

Cards II-VII must accompany each and every configuration even if only one parameter changes. If INPUT = 1 or 3, a number of sets of data cards XVII a&b are used. Consider a test run on four different configurations:

- a. A combination grain with only tabular inputs (no ignition or termination ports, but with weight calculations).

- b. A combination circular perforated and standard star grain with only equation inputs (No termination ports, no ignition, but with weight calculations).
- c. A truncated star grain with two termination ports using both tabular and equation inputs (No ignition, but with weight calculations).
- d. A combination circular perforated and wagon-wheel grain using both tabular and equation inputs (No weight calculations or termination ports, but with ignition calculations).

The correct order for the data cards is:

Configuration a

- 1. I
- 2. II
- 3. III a&b
- 4. IV
- 5. V a&b
- 6. VI a&b
- 7. VII
- 8. VIII a&b (y=0)
- 9. XVI a-e
- 10. XVII a&b (y=y<sub>1</sub>)
- 11. XVII a&b (y=y<sub>2</sub>)
- 12. XVII a&b (y=y<sub>3</sub>)

Configuration c

- 23. II
- 24. III a&b
- 25. IV
- 26. V a&b
- 27. VI a&b
- 28. VII
- 29. VIII a&b (y=0)
- 30. X
- 31. XII
- 32. XIV
- 33. XVI a-e
- 34. XVII a&b (y=y<sub>1</sub>)
- 35. XVII a&b (y=y<sub>2</sub>)
- 36. XVII a&b (y=y<sub>3</sub>)

Configuration b

- 13. II
- 14. III a&b
- 15. IV
- 16. V a&b
- 17. VI a&b
- 18. VII
- 19. IX a&b
- 20. X
- 21. XIII
- 22. XVI a-e

Configuration d

- 37. II
- 38. III a&b
- 39. IV
- 40. V a&b
- 41. VI a&b
- 42. VII
- 43. VIII a&b (y=0)
- 44. IX a&b
- 45. X
- 46. XI
- 47. XV a&b
- 48. XVII a&b (y=y<sub>1</sub>)
- 49. XVII a&b (y=y<sub>2</sub>)
- 50. XVII a&b (y=y<sub>3</sub>)

Note that if a particular data card does not apply, no card is used. For example, XI is omitted for Configuration b. and XII for Configuration d.

#### Program Listing

A complete program listing is presented in Table IV-2.

#### Flowcharts

Flowcharts of the ignition and plotting subroutines for the extended program are presented in Figures IV-4 and IV-5.

TABLE IV-1

DATA CARD FORMATS

cc1	cc10	cc20	cc30	cc40	cc50	cc60	cc70	cc80
				I				
NUMBER OF CONFIGURATIONS TO BE TESTED =--								
				II				
0.0								
				IIIa				
IGO=--	IWO=--							
				IIIb				
IPO=--	NUMPLT(JJ)=--,--,--,--,--,--,--,--,--,--,--							
				IV				
RHO=--	A=--	N=--	ALPHA=--	BETA=--	MU=+-	E+--	CSTAR=--	
				Va				
L=--	TAU=--	DE=--	DTI=--	THETA=--	ALFAN=--			
				Vb				
LTAP=--		XT=--	ZO=--					
				VIa				
DELTAY=--	ZOUT=--	DPOUT=--	ZETA=--	TB=--	HB=--	GAM=--		
				VIb				
RADER=--								
				VII				
INPUT=--	GRAIN=--	STAR=--	NT=--	ORDER=--	COP=--			

TABLE IV-1 (Cont'd)

cc1	cc10	cc20	cc30	cc40	cc50	cc60	cc70	cc80
Y=---		ABPORT=+-E+		VIIla ABSLOT=+-E+		ABNOZ=+-E+		
		APHEAD=+-E+		VIIb APNOZ=+-E+		VCIT=+-E+		
DO=---	DI=---		DELDI=---	IXa S=---		THETAG=---		
LGCI=---	LGNI=---		THETCN=---	IXb THETCH=---				
NS=---	LGSI=---	NP=---	RC=---	X FILLET=---		NN=---		
TAUWW=---	L1=---	L2=---		XI ALPHA1=---		ALPHA2=---		HW=---
RP=---	TAUS=---			XII				
THETAF=---	THETAP=---			XIII TAUWS=---				
LTP=---	DTP=---			XIV THETTP=---		TAUEFF=---		
KA=---	KB=---	UFS=---		XVa CSIG=---		PMIG=---		TI1=---
TI2=---	RRIG=---			XVb PBIG=---				

TABLE IV-1 (Cont'd)

cc1	cc10	cc20	cc30	cc40	cc50	cc60	cc70	cc80
PIPK=-----		DTEMP=-----		XVIa SIGMAP=-----	SIGMAS=-----	N1=-----		
N2=-----		SYCNOM=-----		XVIb DCC=-----	PSIC=-----	DELC=-----		
LCC=-----		NSEG=-----	HCN=-----	XVIc SYNNOM=-----		PSIS=-----		
PSIA=-----		K1=-----	K2=-----	XVI d PSIINS=-----		DELINS=-----		
KEH=-----		KEN=-----	DLINER=-----	XVIe TAUL=-----		WA=-----		
Y=-----		ABPORT=+-E+--		XVIIa ABSLOT=+-E+--		ABNOZ=+-E+--		
		APHEAD=+-E+--		XVIIb APNOZ=+-E+--				



TABLE IV-2

```

C *****
C *
C *      SRM DESIGN AND PERFORMANCE ANALYSIS
C *      PREPARED AT AUBURN UNIVERSITY
C *      UNDER MOD. NO.8 TO COOPERATIVE AGREEMENT WITH
C *      NASA MARSHALL SPACE FLIGHT CENTER
C *
C *      ANALYSIS BY R.H. SFORZINI
C *      PROGRAMMING BY J.M. LYON AND J.E. MURPH
C *      AEROSPACE ENGINEERING DEPARTMENT
C *      APRIL 1973
C *****
      INTEGER GRAIN
      REAL MGEN,MDIS,MNOZ,MN1,JROCK,N,L,ME1,ME,ISP,ITOT,MU,MASS,ISPVAC
      REAL N1,N2,NSEG,K1,K2,KEH,KEN,NS,LCC,LTAP
      REAL M2,MCBAR,ISP2,ITVAC,KA,KB,LAMBDA
      COMMON/CONST1/ZW,AE,AT,THETA,ALFAN
      COMMON/CONST2/CAPGAM,ME,BOT,ZETAF,TB,HB,GAM
      COMMON/CONST3/S,NS,GRAIN
      COMMON/VARIA1/Y,T,DELY,DELTAT,PONZ,PHEAD,RNOZ,RHEAD,SUMAB,PHMAX
      COMMON/VARIA2/ABPORT,ABSLOT,ABNOZ,APHEAD,APNOZ,DADY,ABP2,ABN2,ABS2
      COMMON/VARIA3/ITOT,ITVAC,JROCK,ISP,ISPVAC,MDIS,MNOZ,SG,SUMMT
      COMMON/VARIA4/RNT,RHT,SUM2,R1,R2,R3,RHAVE,RNAVE,RBAR,YB,KOUNT,TL
      COMMON/VARIA5/ABMAIN,ABTD,SUMDY,VC1,VC
      COMMON/IGN1/KA,KB,UFS,RHO,A,N,L,PMIG,TI1,TI2,CSIG
      COMMON/IGN2/ALPHA,BETA,PBIG,RRIG,DELTIG,X,TOP,ZAP
      COMMON/PLUTT/NUMPLT(16),IPO,NDUM,IPT,IOP
      DATA PI,6/3.14159,32.1725/
      READ(5,500) NRUNS
C *****
C *      READ IN THE NUMBER OF CONFIGURATIONS TO BE TESTED
C *****
500 FORMAT(42X,I2)
      IOP=0
      DO 901 I=1,NRUNS
      WRITE(6,602) I
602 FORMAT(1H1,42X,'CONFIGURATION NUMBER ',I2)
      READ(5,499) SUMDY,ANS,ZW,Y,T,DELTAT,RNOZ,RHEAD,SUMAB,PHMAX,SUM2,IT
      IOT,RHT,RNT,R1,R2,R3,RHAVE,RNAVE,RBAR,ITVAC,SUMMT
C *****
C *      SET INITIAL VALUES OF SELECTED VARIABLES EQUAL TO ZERO
C *      ***NOTE*** THESE VALUES MUST BE ZEROED AT THE BEGINNING OF
C *      EACH CONFIGURATION RUN
C *****
499 FORMAT(22F3.1)
      READ(5,491) IGC,IWO
      READ(5,493) IPC,(NUMPLT(JJ),JJ=1,16)
C *****
C *      READ IN THE USER'S OPTIONS
C *****

```

TABLE IV-2. (Cont'd)

```

C *
C * VALUES FOR IGO ARE
C * 0 FOR NO IGNITION TRANSIENT CALCULATIONS
C * 1 FOR IGNITION TRANSIENT CALCULATIONS
C * VALUES FOR IWO ARE
C * 0 FOR NO INERT WEIGHT CALCULATIONS
C * 1 FOR INERT WEIGHT CALCULATIONS
C * VALUES FOR IPO ARE
C * 0 FOR NO PLOTS
C * 1 FOR PLOTS OF EQUILIBRIUM BURNING ONLY
C * 2 FOR PLOTS OF IGNITION TRANSIENT ONLY
C * 3 FOR PLOTS OF BOTH IGNITION TRANSIENT AND
C * EQUILIBRIUM BURNING
C * VALUES FOR NUMPLT(JJ) ARE (NOT REQUIRED FOR IPO=0)
C * 0 IF SPECIFIC PLOT IS NOT DESIRED
C * 1 IF SPECIFIC PLOT IS DESIRED
C * CONTINUE
C * ORDER OF SPECIFICATION OF NUMPLT(JJ) IS
C * 1 PHEAD VS TIME
C * 2 PONOZ VS TIME
C * 3 PHEAD AND PONOZ VS TIME
C * 4 RHEAD VS TIME
C * 5 RNOZ VS TIME
C * 6 RHEAD AND RNOZ VS TIME
C * 7 SUMAB VS TIME
C * 8 SG VS TIME
C * 9 SUMAB AND SG VS TIME
C * 10 F VS TIME
C * 11 FVAC VS TIME
C * 12 F AND FVAC VS TIME
C * 13 VC VS TIME
C * 14 SUMAB VS Y
C * 15 SG VS Y
C * 16 SUMAB AND SG VS Y
C * *****
C 491 FORMAT(4X,I1,9X,I1)
C 493 FORMAT(4X,I1,15X,16(I1,1X))
C WRITE(6,492) IGO,IWO
C WRITE(6,494) IPO,(NUMPLT(JJ),JJ=1,16)
C 492 FORMAT(/,20X,'OPTIONS',/,13X,'IGO= ',I1,/,13X,'IWO= ',I1)
C 494 FORMAT(13X,'IPO= ',I1,/,13X,'NUMPLT(JJ)= ',I1,15(' ',I2))
C READ(5,501) RHO,A,N,ALPHA,BETA,MU,CSTAR
C *****
C * READ IN BASIC PROPELLANT CHARACTERISTICS
C *
C * RHO IS THE DENSITY OF THE PROPELLANT IN SLUGS/IN**3
C * A IS THE BURNING RATE COEFFICIENT
C * N IS THE BURNING RATE EXPONENT

```

TABLE IV-2. (Cont'd)

```

C *      ALPHA AND BETA ARE THE CONSTANTS IN THE EROSION BURNING      *
C *      RELATION OF ROBILLARD AND LENIOR                              *
C *      MU IS THE VISCOSITY OF THE PROPELLANT GASES                    *
C *      CSTAR IS THE CHARACTERISTIC EXHAUST VELOCITY IN FT/SEC        *
C *****
501 FORMAT(4X,F8.6,3X,F6.4,3X,F5.3,7X,F4.1,6X,F5.1,4X,E11.4,7X,F5.0)
    WRITE(6,603) RHO,A,N,ALPHA,BETA,MU,CSTAR
603 FORMAT( //,20X,'PROPELLANT CHARACTERISTICS',/,13X,'RHO= ',F8.6,/,1
13X,'A= ',F6.4,/,13X,'N= ',F5.3,/,13X,'ALPHA= ',F4.1,/,13X,'BETA= '
2,F5.1,/,13X,'MU= ',1PE11.4,/,13X,'CSTAR= ',1PE11.4)
    READ(5,502) L,TAU,DE,DTI,THETA,ALFAN,LTAP,XT,ZO
C *****
C *      READ IN BASIC MOTOR DIMENSIONS                                *
C *
C *      L IS THE TOTAL LENGTH OF THE GRAIN IN INCHES                    *
C *      TAU IS THE AVERAGE WEB THICKNESS OF THE CONTROLLING GRAIN      *
C *      LENGTH IN INCHES                                                *
C *      DE IS THE DIAMETER OF THE NOZZLE EXIT IN INCHES                *
C *      DTI IS THE INITIAL DIAMETER OF THE NOZZLE THROAT IN INCHES     *
C *      THETA IS THE CANT ANGLE OF THE NOZZLE WITH RESPECT TO THE      *
C *      MOTOR AXIS IN RADIANS                                           *
C *      ALFAN IS THE EXIT HALF ANGLE OF THE NOZZLE IN RADIANS          *
C *      LTAP IS THE LENGTH OF THE GRAIN AT THE NOZZLE END HAVING      *
C *      ADDITIONAL TAPER NOT REPRESENTED BY ZO IN INCHES              *
C *      XT IS THE DIFFERENCE IN WEB THICKNESS ASSOCIATED WITH LTAP     *
C *      ZO IS THE INITIAL DIFFERENCE BETWEEN WEB THICKNESSES AT THE    *
C *      HEAD AND AFT ENDS OF THE CONTROLLING GRAIN LENGTH              *
C *****
502 FORMAT(2X,F5.0,5X,F5.2,4X,F6.2,5X,F6.2,7X,F6.4,7X,F6.4,/,10X,
1 F6.2,4X,F5.2,4X,F5.2)
    WRITE(6,604) L,TAU,DE,DTI,THETA,ALFAN,LTAP,XT,ZO
604 FORMAT(//,20X,'BASIC MOTOR DIMENSIONS',/,13X,'L= ',F5.0,/,13X,'TAU
1= ',F5.2,/,13X,'DE= ',
21PE11.4,/,13X,'DTI= ',1PE11.4,/,13X,'THETA= ',1PE11.4,/,13X,'ALFAN=
3 ',1PE11.4,/,13X,'LTAP= ',1PE11.4,/,13X,'XT= ',1PE11.4,/,13X,'ZO=
4 ',1PE11.4)
    READ(5,503) DELTAY,XOUT,DPOUT,ZETAF,TB,HB,GAM,RADER
C *****
C *      READ IN BASIC PERFORMANCE CONSTANTS                            *
C *
C *      DELTAY IS THE DESIRED BURN INCREMENT DURING TAILOFF IN INCHES  *
C *      XOUT IS THE DISTANCE BURNED IN INCHES AT WHICH THE PROPELLANT  *
C *      BREAKS UP                                                        *
C *      DPOUT IS THE DEPRESSURIZATION RATE IN LB/IN**3 AT WHICH THE    *
C *      PROPELLANT IS EXTINGUISHED                                      *
C *      ZETAF IS THE THRUST LOSS COEFFICIENT                            *
C *      TB IS THE ESTIMATED BURN TIME IN SECONDS                       *
C *      HB IS THE ESTIMATED BURNOUT ALTITUDE IN FEET                    *

```

TABLE IV-2. (Cont'd)

```

C *      GAM IS THE RATIO OF SPECIFIC HEATS FOR THE PROPELLANT GASES *
C *      RADER IS THE RADIAL EROSION RATE OF THE NOZZLE THROAT IN *
C *      INCHES/SEC *
C *****
503 FORMAT(7X,F5.3,6X,F7.2,7X,F7.2,7X,F4.3,4X,F5.1,4X,F7.0,5X,F5.3,/,8
1X,F6.4)
WRITE(6,606) DELTAY,XOUT,DPOUT,ZETAF,TB,HB,GAM,RADER
606 FORMAT(/,20X,'BASIC PERFORMANCE CONSTANTS',/,13X,'DELTAY= ',F5.3,
1/,13X,'XOUT= ',F7.2,/,13X,'DPOUT= ',F7.2,/,13X,'ZETAF= ',F5.3,/,13
2X,'TB= ',F5.1,/,13X,'HB= ',F7.0,/,13X,'GAM= ',F5.3,/,13X,'RADER= '
3,F6.4)
NDUM=0
IPT=0
MN1=.85
ME1=7.0
Z=ZO
S=0.0
NS=0.0
KOUNT=0
ABMAIN=0.0
ABTO=0.0
DELY=DELTAY
TOP=GAM+1.
BOT=GAM-1.
ZAP=TOP/(2.*BOT)
CAPGAM=SQRT(GAM)*(2./TOP)**ZAP
AE=PI*DE*DE/4.
1 IF(XT.LE.0.0) TL=0.0
IF(XT.LE.0.0) GO TO 40
TL=(Y-TAU+XT+Z/2.)*LTAP/XT
IF(TL.LE.0.0) TL=0.0
IF(TL.GE.LTAP) TL=LTAP
40 DT=DT1+2.*(RADER*T)
AT=PI*DT*DT/4.
CALL AREAS
IF(Y.LE.0.0) VC=VCI
IF(ABS(ZW).GT.0.0) GO TO 20
IF(SUMAB.LE.0.0) GO TO 31
X=(ABPORT+ABSLOT)/SUMAB
90 MNOZ=AT*X/APNOZ*(2.*(1.+BOT/2.*MN1*MN1)/TOP)**ZAP
IF(ABS(MNOZ-MN1).LE.0.002) GO TO 2
MN1=MNOZ
GO TO 90
2 VNOZ=GAM*CSTAR*MNOZ*SQRT(((2./TOP)**(TOP/BOT))/(1.+BOT/2.*MNOZ*MNO
1Z))
PRAT=(1.+BOT/2.*MNOZ*MNOZ)**(-GAM/BOT)
JROCK=AT/APNOZ
IF(IGO.EQ.0.OR.Y.GT.0.0) GO TO 900

```

TABLE IV-2. (Cont'd)

```

      READ(5,97) KA,KB,UFS,CSIG,PMIG,TI1,TI2,RRIG,DELTIG,PBIG
C *****
C *   READ IN VALUES REQUIRED FOR IGNITION CALCULATIONS
C *   ***NOTE*** NOT REQUIRED IF IGO=0
C *
C *   KA AND KB DEFINE THE CHARACTERISTIC VELOCITY IN FT/SEC
C *   CSTR = KA + KB * PRESSURE
C *   UFS IS THE FLAME-SPREADING SPEED IN IN/SEC
C *   CSIG IS THE CHARACTERISTIC VELOCITY OF THE IGNITER IN FT/SEC
C *   PMIG IS THE MAXIMUM IGNITER PRESSURE IN LBS/IN**2
C *   TI1 IS THE TIME OF MAXIMUM IGNITER PRESSURE IN SECONDS
C *   TI2 IS THE TIME(IN SECONDS) FOR THE IGNITER PRESSURE TO
C *   DROP TO 10 PER CENT OF MAXIMUM VALUE(PMIG)
C *   RRIG IS THE AVERAGE REGRESSION RATE OF THE FIRST HALF OF THE
C *   IGNITER PRESSURE TIME TRACE IN LBS/IN**2/SEC
C *   DELTIG IS THE TIME INCREMENT FOR IGNITION TRANSIENT
C *   CALCULATIONS IN SECONDS
C *   PBIG IS THE BLOWOUT PRESSURE OF THE MAIN MOTOR BLOWOUT PLUG
C *   IN LBS/IN**2
C *****
97  FORMAT(3X,F7.1,5X,F5.3,6X,F7.1,7X,F7.1,7X,F7.1,6X,F5.3,/,4X,F5.2,
1    7X,F7.1,9X,F5.3,7X,F7.3)
      WRITE(6,842) KA,KB,UFS,CSIG,PMIG,TI1,TI2,RRIG,DELTIG,PBIG
842  FORMAT(20X,'IGNITION CONSTANTS',/,13X,'KA= ',F7.1,/,13X,'KB= ',
1    F5.3,/,13X,'UFS= ',F7.1,/,13X,'CSIG= ',F7.1,/,13X,'PMIG= ',
1    F7.1,/,13X,'TI1= ',F5.3,/,13X,'TI2= ',F5.2,/,13X,'RRIG= ',
1    F7.1,/,13X,'DELTIG= ',F5.3,/,13X,'PBIG= ',F7.3,/)
900  IF(IWO.EQ.0.OR.Y.GT.0.0) GO TO 832
      READ(5,600) PIPK,DTEMP,SIGMAP,SIGMAS,N1,N2,SYCNOM,DCC,PSIC,DELC,LC
1C,NSEG,HCN,SYNNOM,PSIS,PSIA,K1,K2,PSIINS,DELINS,KEH,KEN,DLINER,TAU
2L,WA
C *****
C *   READ IN BASIC PROPERTIES REQUIRED FOR WEIGHT CALCULATIONS
C *   ***NOTE*** NOT REQUIRED IF IWO=0
C *
C *   PIPK IS THE TEMPERATURE SENSITIVITY COEFFICIENT OF PRESSURE
C *   AT CONSTANT K
C *   DTEMP IS THE MAX EXPECTED INCREASE IN TEMPERATURE ABOVE
C *   CONDITIONS UNDER WHICH MAIN TRACE WAS CALCULATED IN
C *   DEGREES FAHRENHEIT
C *   SIGMAP IS THE VARIATION IN PHMAX
C *   SIGMAS IS THE VARIATION IN CASE MATERIAL YIELD STRENGTH
C *   N1 IS THE NUMBER OF STANDARD DEVIATIONS IN PHMAX TO BE USED
C *   AS A BASIS FOR DESIGN
C *   N2 IS THE NUMBER OF STANDARD DEVIATIONS IN SY TO BE USED AS
C *   A BASIS FOR DESIGN
C *   SYCNOM IS THE NOMINAL YIELD STRENGTH OF THE CASE MATERIAL
C *   IN LBS/INCH

```

TABLE IV-2. (Cont'd)

```

C *   DCC IS THE ESTIMATED MEAN DIAMETER OF THE CASE IN INCHES *
C *   PSIC IS THE SAFETY FACTOR ON THE CASE THICKNESS *
C *   DELC IS THE SPECIFIC WEIGHT OF THE CASE MATERIAL IN LBS/IN**3 *
C *   LCC IS THE LENGTH OF THE CYLINDRICAL PORTION OF THE CASE *
C *   INCLUDING FORWARD AND AFT SEGMENTS IN INCHES *
C *   NSEG IS THE NUMBER OF CASE SEGMENTS *
C *   HCN IS THE AXIAL LENGTH OF THE NOZZLE CLOSURE IN INCHES *
C *   SYNOM IS THE NOMINAL YIELD STRENGTH OF THE NOZZLE MATERIAL *
C *   IN LBS/INCH *
C *   CONTINUE *
C *   PSIS IS THE SAFETY FACTOR ON THE NOZZLE STRUCTURAL MATERIAL *
C *   PSIA IS THE SAFETY FACTOR ON THE NOZZLE ABLATIVE MATERIAL *
C *   K1 AND K2 ARE EMPIRICAL CONSTANTS IN THE NOZZLE WT. EQUATION *
C *   PSIINS IS THE SAFETY FACTOR ON NOZZLE INSULATION *
C *   DELINS IS THE SPECIFIC WEIGHT OF THE INSULATION IN LBS/IN**3 *
C *   KEH IS THE EROSION RATE OF INSULATION TAKEN CONSTANT *
C *   EVERYWHERE EXCEPT AT THE NOZZLE CLOSURE IN IN/SEC *
C *   KEN IS THE EROSION RATE OF INSULATION AT THE NOZZLE CLOSURE *
C *   IN IN/SEC *
C *   DLINER IS THE SPECIFIC WEIGHT OF THE LINER IN LBS/IN**3 *
C *   TAUL IS THE THICKNESS OF THE LINER IN INCHES *
C *   WA IS ANY ADDITIONAL WEIGHT NOT CONSIDERED ELSEWHERE IN LBS *
C *****
600 FORMAT(7X,F5.4,9X,F6.2,10X,F5.3,10X,F5.3,6X,F5.2,/,5X,F5.2,10X,F10
1.2,7X,F6.2,8X,F5.2,8X,F5.3,/,6X,F7.2,8X,F3.0,7X,F4.1,10X,F10.2,8X,
2F5.2,/,7X,F5.2,6X,F6.4,6X,F6.4,10X,F5.2,10X,F6.4,/,6X,F6.4,7X,F6.4
3,10X,F6.4,8X,F6.4,6X,F7.2)
WRITE(6,610) PIPK, DTEMP, SIGMAP, SIGMAS, N1, N2, SYNOM, DCC, PSIC, DELC, L
ICC, NSEG, HCN, SYNOM, PSIS, PSIA, K1, K2, PSIINS, DELINS, KEH, KEN, DLINER, TA
2UL, WA
610 FORMAT( 20X, 'INERT WEIGHT INPUTS',/,13X, 'PIPK= ',1PE11.4,/,13X, '
1DTEMP= ',1PE11.4,/,13X, 'SIGMAP= ',1PE11.4,/,13X, 'SIGMAS= ',1PE11.4
2,/,13X, 'N1= ',1PE11.4,/,13X, 'N2= ',1PE11.4,/,13X, 'SYNOM= ',1PE11.
34,/,13X, 'DCC= ',1PE11.4,/,13X, 'PSIC= ',1PE11.4,/,13X, 'DELC= ',1PE1
41.4,/,13X, 'LCC= ',1PE11.4,/,13X, 'NSEG= ',1PE11.4,/,13X, 'HCN= ',1PE
511.4,/,13X, 'SYNOM= ',1PE11.4,/,13X, 'PSIS= ',1PE11.4,/,13X, 'PSIA=
6',1PE11.4,/,13X, 'K1= ',1PE11.4,/,13X, 'K2= ',1PE11.4,/,13X, 'PSIINS=
7',1PE11.4,/,13X, 'DELINS= ',1PE11.4,/,13X, 'KEH= ',1PE11.4,/,13X, 'K
8EN= ',1PE11.4,/,13X, 'DLINER= ',1PE11.4,/,13X, 'TAUL= ',1PE11.4,/,13
9X, 'WA= ',1PE11.4)
832 SUMYA=DELY*(ABP2+ABN2+ABS2)
IF(Y.EQ.0.0) SUMYA=0.0
VC=VC+SUMYA
IF(Y.GT.0.0) GO TO 11
PONOZ=(A*RHO*CSTAR*SUMAB/AT)**(1./(1.-N))*(1.+(CAPGAM*JROCK)**2/2.
1)**(N/(1.-N))
PON=PONOZ
MOIS=AT*PONOZ/CSTAR

```

TABLE IV-2. (Cont'd)

```

P2=PON0Z
PON0Z2=PON0Z
PNOZ=PRAT*PON0Z
P4=2.*MDIS*VNOZ/(APHEAD+APNOZ)+PNOZ
IF(GRAIN.EQ.3) P4=MDIS*VNOZ/APNOZ+PNOZ
5 PNOZ=PRAT*PON0Z
PHEAD=2.*MDIS*VNOZ/(APHEAD+APNOZ)+PNOZ
IF(GRAIN.EQ.3) PHEAD=MDIS*VNOZ/APNOZ+PNOZ
RHEAD=A*PHEAD**N
ZIT=MDIS*X/APNOZ
RN1=RHEAD
PHEAD2=PHEAD
3 RNOZ=RN1-((RN1-A*PNOZ**N-ALPHA*ZIT**.8/(L**.2*EXP(BETA*RN1*RHO/ZIT
1))))/(1.+ALPHA*ZIT**.8*BETA*RHO/ZIT/(L**.2*EXP(BETA*RN1*RHO/ZIT))))
IF(ABS(RN1-RNOZ).LE.0.002) GO TO 4
RN1=RNOZ
GO TO 3
4 AVE1=(RHEAD+RNOZ)/2.
IF(Y.GT.0.0) GO TO 7
RN2=RNOZ
RH2=RHEAD
PONJ=PON0Z
OPCDY=0.0
AVE2=AVE1
7 RNAVE=(RNOZ+RN2)/2.
RHAVE=(RHEAD+RH2)/2.
MGEN=RHO/2.*((RNOZ+RHEAD)*(ABPORT+ABSLOT)+2.*A*PON0Z**N*ABNOZ)
DRDY=(AVE1-AVE2)/DELY
RRAR=(AVE1+AVE2)/2.
GMAX=1.002*MDIS
GMIN=0.998*MDIS
IF(Y.GT.0.0) GO TO 12
GMAX=1.001*MDIS
GMIN=0.999*MDIS
IF(MGEN.GE.GMIN.AND.MGEN.LE.GMAX) GO TO 6
MDIS=MGEN
PON0Z=MDIS*CSTAR/AT
GO TO 5
6 RE=2.*MDIS*X*L/((APNOZ+APHEAD)*MU)
17 ME=SQR(2./BOT*(TOP/2.*(AE*ME1/AT)**(1./ZAP)-1.))
IF(ABS(ME-ME1).LE.0.002) GO TO 9
ME1=ME
GO TO 17
9 CONTINUE
IF(IGO.NE.0.AND.Y.LE.0.0) CALL IGNITN
IF(Y.LE.0.0) WRITE(6,101) RE
101 FORMAT(///,33X,'*****',/,33X,'***** EQUILIB
IRIUM BURNING *****',/,33X,'*****',/,33X,

```

TABLE IV-2. (Cont'd)

```

1  INITIAL REYNOLDS NUMBER= ',1PE11.4)
   PONJ=PONQZ
   CALL OUTPUT
10 IF(Y.LE..05*TAU) GO TO 16
   SINK1=VC/((CAPGAM*CSTAR)**2*RBAR*DPCDY/12.
   MASS=.01*MDIS
   ANS4=Y+10.0*DELTAY
   IF(KOUNT.GT.0) GO TO 16
   IF(ABS(SINK1).LE.MASS.AND.ANS4.LE.ANS-XT) GO TO 18
   GO TO 16
18 DELY=10.*DELTAY
   GO TO 55
16 DELY=DELTAY
55 DELTAT=2.*DELY/(RHAVE+RNAVE)
   Z=Z+DELTAT*(RNAVE-RHAVE)
   Y=Y+DELY
   T=T+DELTAT
   SUM2=SUMAB
   RN2=RNOZ
   RH2=RHEAD
   AVE2=AVE1
   GO TO 1
11 MDIS=AT*PONQZ/CSTAR
   GO TO 5
12 DPCDY=(PHEAD2+PCNOZ2)/(RNAVE+RHAVE)*DRDY+(PHEAD2+PONQZ2)/((ABP2+AB
1N2+ABS2)*2.)*DADY
   IF(ABS(DPCDY).GE.DPCDY.OR.Y.GE.XOUT) GO TO 25
   SINK1=VC/((CAPGAM*CSTAR)**2*RBAR*DPCDY/12.+(PHEAD2+PONQZ2)/2.*(RNAV
1E+RHAVE)/2.*(ABP2+ABN2+ABS2)/(12.*(CSTAR*CAPGAM)**2)
   STUFF=MGEN-SINK1
   IF(STUFF.GE.GMIN.AND.STUFF.LE.GMAX) GO TO 14
   MDIS=STUFF
   PONQZ=MDIS*CSTAR/AT
   GO TO 5
14 P1=PONQZ
   PONJ=PONQZ
   PONQZ2=(P1+P2)/2.
   P2=PONQZ
   P3=PHEAD
   PHEAD2=(P3+P4)/2.
   P4=PHEAD
   ANS=TAU-ABS(Z/2.)
   IF(Y.LT.ANS) CALL OUTPUT
   IF(Y.LT.ANS) GO TO 10
19 ZW=Z
   YW=Y
   SUMBA=SUMAB
   P1=PONQZ

```



TABLE IV-2. (Cont'd)

```

KH2=RHEAD
RN2=RNOZ
RAVE=AVE1
ABMAIN=SUMAB
ABTO=0.0
WRITE(6,51)
51 FORMAT(/,37X,'*****',/,37X,'***** TAIL OFF BEG
1INS ****',/,37X,'*****',/)
20 ANS2=TAU+ABS(ZW/2.)
KOUNT=KOUNT+1
DELYW=DELTAY
DY2=DELYW
IF(ZW) 32,32,33
32 IF(Y.LT.ANS2.AND.ABS(ZW).GT.DY2) GO TO 211
SUMAB=ABMAIN
GO TO 31
211 SUMDY=SUMDY+DELYW
SUMAB=(1.+SUMDY/ZW-DELYW/(2.*ZW))*ABTO-(SUMDY/ZW-DELYW/(2.*ZW))*AB
1MAIN
GO TO 31
33 IF(Y.LT.ANS2.AND.ZW.GT.DY2) GO TO 21
SUMAB=ABTO
GO TO 31
21 SUMDY=SUMDY+DELYW
SUMAB=(1.-SUMDY/ZW+DELYW/(2.*ZW))*ABMAIN+(SUMDY/ZW-DELYW/(2.*ZW))*
1ABTO
31 IF(SUMAB.LE.0.0) PONOZ=PONOZ/2.
IF(SUMAB.LE.0.0) GO TO 25
PONOZ=(A*RHO*CSTAR*SUMAB/AT)**(1./(1.-N))
MDIS=AT*PONOZ/CSTAR
ABAVE=(SUMAB+SUMBA)/2.
SUMYA=DELY*ABAVE
VC=VC+SUMYA
DADY=(SUMAB-SUMBA)/DELY
PBAR=(P1+PONOZ)/2.
SUMBA=SUMAB
22 DPCDY=PBAR/(1.-N)*1./ABAVE*DADY
IF(PONOZ.LE.30.0) GO TO 25
RNOZ=A*PONOZ*N
RHEAD=RNOZ
RBAR=(RHEAD+RAVE)/2.
MGEN=RHO*(RNOZ+RHEAD)/2.*SUMAB
GMAX=1.002*MDIS
GMIN=0.998*MDIS
SINK1=VC/(CAPGAM*CSTAR)**2*RBAR*DPCDY/12.
STUFF=MGEN-SINK1
IF(STUFF.GE.GMIN.AND.STUFF.LE.GMAX) GO TO 23
MDIS=STUFF

```

TABLE IV-2. (Cont'd)

```

PONDZ=PCNJ+DPCDY*DELY
IF(PONDZ.LE.0.0) PONDZ=0.0
PBAR=(P1+PONDZ)/2.
GO TO 22
23 RHAVE=(RH2+RHEAD)/2.
RNAVE=(RN2+RNOZ)/2.
RH2=RHEAD
RN2=RNOZ
PHEAD=PONDZ
RAVE=RHEAD
P1=PONDZ
PCNJ=PONDZ
IF(ABS(DPCDY).GE.DPOUT) GO TO 25
IF(Y.GE.XOUT) GO TO 25
CALL OUTPUT
GO TO 10
25 SUMAB=0.0
RHEAD=0.0
RNOZ=RHEAD
PHEAD=PONDZ
WRITE(6,318)
318 FORMAT(/,33X,'*****',/,33X,'**** BEGI
IN HALF SECOND TRACE ****',/,33X,'*****
1')
CALL OUTPUT
TIME=T
DELTAT=.5
TIM=TIME+.5.
PHT=PHEAD
PONT=PONDZ
SG=0.0
29 T=T+DELTAT
PHEAD=PHT/EXP(CAPGAM**2*AT*CSTAR/VC*(T-TIME)*12.)
PONDZ=PHEAD
MDIS=PONDZ*AT/CSTAR
Y=Y+.5*RHEAD
CALL OUTPUT
28 IF(T.LT.TIM.AND.PHEAD.GE.30.0) GO TO 29
100 WP1=G*SUMMT
WP2=RHO*(VC-VC1)*G
WP=(WP1+WP2)/2.
ISP=ITOT/WP
ISPVAC=ITVAC/WP
WRITE(6,102) WP1,WP2,WP,PHMAX,ISP,ISPVAC,ITOT,ITVAC
102 FORMAT(///,13X,'WP1= ',1PE11.4,/,13X,'WP2= ',1PE11.4,/,13X,'WP= ',
11PE11.4,/,13X,'PHMAX= ',1PE11.4,/,13X,'ISP= ',1PE11.4,/,13X,'ISPVA
2C= ',1PE11.4,/,13X,'ITOT= ',1PE11.4,/,13X,'ITVAC= ',1PE11.4)
LAMBDA=(VC-VC1)/VC

```

TABLE IV-2. (Cont'd)

```

WRITE(6,103) VCI,VC,LAMBDA
103 FORMAT(13X,'VCI= ',1PE11.4,/,13X,'VCF= ',1PE11.4,/,13X,'LAMBDA= ',
1 1PE11.4)
IF(IWO.EQ.0) GO TO 903
PMEOP=PHMAX*(1.+N1*SIGMAP)*EXP(PIPK*DTMP)
SYC=SYCNOM*(1.-N2*SIGMAS)
TAUCC=PSIC*PMEOP*DCC/(2.*SYC)
WCC=PI*TAUCC*DCC*DELC*LCC*(1.+(NSEG-1.)*(40.*TAUCC/LCC))
TAUCD=TAUCC/2.
WCH=2.5*PI/2.*DCC*DCC*TAUCD*DELC
WCN=4.5*PI/2.*DCC*HCN*TAUCD*DELC
WC=WCC+WCH+WCN
EPSIL=AE/AT
DT=2.*SQRT(AT/PI)
WN=K1*DT*DT/(1.+5*SIN(ALFAN))*((EPSIL-SQRT(EPSIL))*PMEOP*DT*PSIS/
1SYNNOM+K2*T*PSIA)
WINS=T*PSIINS*DELINS*DCC*PI*(KEH*(DCC*.40+(S+NS)*TAU/2.+0.15/
1PSIINS*(LCC-TAU*(S+NS)))+KEN*.80*HCN)
WL=TAUL*DLINER*PI*DCC*(DCC/2.+LCC+HCN)
WM=WC+WN+WINS+WL+WA+WP
ZETAM=WP/WM
RATIO=ITOT/WM
WRITE(6,605)
605 FORMAT(///,20X,'MOTOR WEIGHT CALCULATIONS')
WRITE(6,601) PMEOP,TAUCC,WC,WN,WINS,WL,WM,ZETAM,RATIO
601 FORMAT(13X,'MAX EXPECTED PRESSURE= ',1PE11.4,/,13X,'CYLINDRICAL CA
1SE THICKNESS= ',1PE11.4,/,13X,'CASE WT= ',1PE11.4,/,13X,'NOZZLE WT
2= ',1PE11.4,/,13X,'INSULATION WT= ',1PE11.4,/,13X,'LINER WT= ',1PE
311.4,/,13X,'TOTAL MOTOR WT= ',1PE11.4,/,13X,'ZETAM= ',1PE11.4,/,13
4X,'RATIO OF ITOT TO WM= ',1PE11.4)
903 CONTINUE
▶ NDUM=1
▶ IF(IPO.NE.0.AND.IPO.NE.2) CALL OUTPUT
901 CONTINUE
▶ IF(IOP.NE.0) CALL PLOT(0.0,0.0,999)
STOP
END

```

TABLE IV-2. (Cont'd)

```

SUBROUTINE AREAS
C *****
C * SUBROUTINE AREAS CALCULATES BURNING AREAS AND PORT AREAS FOR *
C * CIRCULAR PERFORATED (C.P.) GRAINS AND STAR GRAINS OR FOR A *
C * COMBINATION OF C.P. AND STAR GRAINS *
C *****
      INTEGER STAR, GRAIN, ORDER, COP
      REAL MGEN, MDIS, MNOZ, MN1, JROCK, N, L, ME1, ME, ISP, ITOT, MU, MASS, ISPVAC
      REAL LGCI, LGNI, NS, NN, NP, LGS1, NT, LTP, LGC, LS, LF
      REAL M2, MDBAR, ISP2, ITVAC, L1, L2, LFW, LFWSQD
      COMMON/CONST1/ZW, AE, AT, THETA, ALFAN
      COMMON/CONST3/S, NS, GRAIN
      COMMON/VAR1A1/Y, T, DELY, DELTAT, PNOZ, PHEAD, RNOZ, RHEAD, SUMAB, PHMAX
      COMMON/VAR1A2/ABPORT, ABSLOT, ABNOZ, APHEAD, APNOZ, DADY, ABP2, ABN2, ABS2
      COMMON/VAR1A3/ITOT, ITVAC, JROCK, ISP, ISPVAC, MDIS, MNOZ, SG, SUMMT
      COMMON/VAR1A4/RNT, RHT, SUM2, R1, R2, R3, RHAVE, RNAME, RBAR, YB, KOUNT, TL
      COMMON/VAR1A5/ABMAIN, ABTO, SUMDY, VCI, VC
      DATA PI/3.14159/
      ABPC=0.0
      ABNC=0.0
      ABSC=0.0
      ABPS=0.0
      ABNS=0.0
      A3SS=0.0
      DABT=0.0
      SG=0.0
      ANUM=PI/4.
      PID2=PI/2.
      RNT=RNT+RNOZ*DELTAT
      RHT=RHT+RHEAD*DELTAT
      IF(Y.LE.0.0) AGS=0.0
1 K=0
      IF(ABS(ZW).GT.0.0) K=1
      YB=Y
      IF(K.EQ.1) Y=YB-SUMDY/2.
2 IF(K.EQ.2) Y=YB+ABS(ZW)/2.-SUMDY/2.
      IF(Y.LE.0.0) READ(5,500) INPUT, GRAIN, STAR, NT, ORDER, COP
C *****
C * READ THE TYPE OF INPUT FOR THE PROGRAM AND THE BASIC GRAIN *
C * CONFIGURATION AND ARRANGEMENT *
C * VALUES FOR INPUT ARE *
C * 1 FOR ONLY TABULAR INPUT *
C * 2 FOR ONLY EQUATION INPUTS (EQUATIONS ARE BUILT *
C * INTO THE SUBROUTINE) *
C * 3 FOR A COMBINATION OF 1 AND 2 *
C * VALUES FOR GRAIN ARE *
C * 1 FOR STRAIGHT C.P. GRAIN *
C * 2 FOR STRAIGHT STAR GRAIN *

```

TABLE IV-2. (Cont'd)

```

C *          3 FOR COMBINATION OF C.P. AND STAR GRAINS *
C *  VALUES FOR STAR ARE (WAGON WHEEL IS CONSIDERED A TYPE OF *
C *    STAR GRAIN IN THIS PROGRAM) *
C *          0 FOR STRAIGHT C.P. GRAIN *
C *          1 FOR STANDARD STAR *
C *          2 FOR TRUNCATED STAR *
C *          3 FOR WAGON WHEEL *
C *  VALUES FOR NT ARE *
C *          0 IF THERE ARE NO TERMINATION PORTS *
C *          X WHERE X IS THE NUMBER OF TERMINATION PORTS *
C *  VALUES OF ORDER ESTABLISH HOW A COMBINATION C.P. AND STAR *
C *    GRAIN IS ARRANGED *
C *          1 IF DESIGN IS STAR AT HEAD END AND C.P. AT NOZZLE *
C *          2 IF DESIGN IS C.P. AT HEAD END AND C.P. AT NOZZLE *
C *          3 IF DESIGN IS C.P. AT HEAD END AND STAR AT NOZZLE *
C *          4 IF DESIGN IS STAR AT HEAD END AND STAR AT NOZZLE *
C *          ***NOTE*** IF GRAIN=1, VALUE OF ORDER MUST BE 2 *
C *          ***NOTE*** IF GRAIN=2, VALUE OF ORDER MUST BE 4 *
C *  CONTINUE *
C *  VALUES FOR COP ARE (APPLICABLE TO C.P. GRAINS ONLY) *
C *          0 IF BOTH ENDS ARE CONICAL OR FLAT *
C *          1 IF HEAD END IS CONICAL OR FLAT AND AFT END IS *
C *            HEMISPHERICAL *
C *          2 IF BOTH ENDS ARE HEMISPHERICAL *
C *          3 IF HEAD END IS HEMISPHERICAL AND AFT END IS *
C *            CONICAL OR FLAT *
C *  ***** *
500 FORMAT(9X,I2,9X,I2,8X,I2,6X,F4.0,9X,I2,7X,I2)
      IF(Y.LE.0.0) WRITE(6,607)
607 FORMAT(/,20X,'GRAIN CONFIGURATION')
      IF(Y.LE.0.0) WRITE(6,600) INPUT,GRAIN,STAR,NT,ORDER,COP
600 FORMAT(13X,'INPUT= ',I2,/,13X,'GRAIN= ',I2,/,13X,'STAR= ',I2,/,13X
1,'NT= ',F4.0,/,13X,'ORDER= ',I2,/,13X,'COP= ',I2,/)
      IF(INPUT.EQ.2) GO TO 12
      IF(Y.LE.0.0) GO TO 6
      IF(YT.LE.Y.AND.K.LT.2) GO TO 8
9  DENOM=YT-YT2
      SLOPE1=(ABPK-ABPK2)/DENOM
      SLOPE2=(ABSK-ABSK2)/DENOM
      SLOPE3=(ABNK-ABNK2)/DENOM
      SLOPE4=(APHK-APHK2)/DENOM
      SLOPE5=(APNK-APNK2)/DENOM
      B1=ABPK-SLOPE1*YT
      B2=ABSK-SLOPE2*YT
      B3=ABNK-SLOPE3*YT
      B4=APHK-SLOPE4*YT
      B5=APNK-SLOPE5*YT
      ABPT=SLOPE1*Y+B1

```

TABLE IV-2. (Cont'd)

```

ABST=SLOPE2*Y+B2
ABNT=SLOPE3*Y+B3
APHT=SLOPE4*Y+B4
APNT=SLOPE5*Y+B5
IF(INPUT.EQ.3) GO TO 3
GO TO 52
6 READ(5,507) YT,ABPK,ABSK,ABNK,APHK,APNK,VCIT
C *****
C * READ IN TABULAR VALUES FOR Y=0.0 (NOT REQUIRED IF INPUT=2) *
C *
C * ABPK IS THE BURNING AREA IN THE PORT IN IN**2 *
C * ABSK IS THE BURNING AREA IN THE SLOTS IN IN**2 *
C * ABNK IS THE BURNING AREA IN THE NOZZLE END IN IN**2 *
C * APHK IS THE PORT AREA AT THE HEAD END IN IN**2 *
C * APNK IS THE PORT AREA AT THE NOZZLE END IN IN**2 *
C * VCIT IS THE INITIAL VOLUME OF CHAMBER GASES ASSOCIATED WITH *
C * TABULAR INPUT IN IN**3 *
C *****
507 FORMAT(6X,F6.2,10X,E11.4,10X,E11.4,8X,E11.4,/,22X,E11.4,9X,E11.4,
1 8X,E11.4)
WRITE(6,610)
610 FORMAT(13X,'TABULAR VALUES FOR YT EQUAL ZERO READ IN')
WRITE(6,583) ABPK,ABSK,ABNK,APHK,APNK
583 FORMAT(13X,'ABPK=',1PE11.4,5X,'ABSK=',1PE11.4,5X,'ABNK=',1PE11.4,
1 5X,'APHK=',1PE11.4,5X,'APNK=',1PE11.4)
WRITE(6,584) VCIT
584 FORMAT(13X,'VCIT=',1PE11.4,/)
ABPT=ABPK
ABST=ABSK
ABNT=ABNK
APHT=APHK
APNT=APNK
YT2=YT
IF(INPUT.EQ.3) GO TO 3
GO TO 52
8 YT2=YT
ABPK2=ABPK
ABNK2=ABNK
ABSK2=ABSK
APHK2=APHK
APNK2=APNK
READ(5,505) YT,ABPK,ABSK,ABNK,APHK,APNK
C *****
C * READ IN TABULAR VALUES FOR Y=Y (NOT REQUIRED FOR INPUT=2) *
C *****
505 FORMAT(6X,F6.2,10X,E11.4,10X,E11.4,8X,E11.4,/,22X,E11.4,9X,E11.4)
WRITE(6,611) YT
611 FORMAT(///,13X,'TABULAR VALUES FOR YT= ',F7.3,' READ IN')

```

TABLE IV-2. (Cont'd)

```

WRITE(6,583) ABPK,ABSK,ABNK,APHK,APNK
GU TO 9
12 ABPT=0.0
   ABNT=0.0
   ABST=0.0
3  IF(GRAIN.NE.2) GO TO 4
   ABPC=0.0
   ABNC=0.0
   ABSC=0.0
   GO TO 7
4  IF(Y.LE.0.0) READ(5,501) DO,DI,DELDI,S,THETAG,LGCI,LGNI,THETCN,THE
   TCH
C  *****
C  *      READ IN BASIC GEOMETRY FOR C.P. GRAIN (NOT REQUIRED FOR      *
C  *      STRAIGHT STAR GRAIN)                                         *
C  *      DO IS THE AVERAGE OUTSIDE INITIAL GRAIN DIAMETER IN INCHES  *
C  *      DI IS THE AVERAGE INITIAL INTERNAL GRAIN DIAMETER IN INCHES *
C  *      DELDI IS THE DIFFERENCE BETWEEN THE INITIAL INTERNAL GRAIN   *
C  *      DIAMETER AT THE NOZZLE END AND DI IN INCHES                  *
C  *      S IS THE NUMBER OF FLAT BURNING SLOT SIDES (NOT INCLUDING     *
C  *      THE NOZZLE END)                                              *
C  *      THETAG IS THE ANGLE THE NOZZLE END OF THE GRAIN MAKES WITH   *
C  *      THE MOTOR AXIS IN RADIANS                                    *
C  *      LGCI IS THE INITIAL TOTAL LENGTH OF THE CIRCULAR PERFORATION *
C  *      IN INCHES                                                    *
C  *      LGNI IS THE INITIAL SLANT LENGTH OF THE BURNING CONICAL     *
C  *      GRAIN AT THE NOZZLE END IN INCHES                           *
C  *      THETCN IS THE CONTRACTION ANGLE OF THE BONDED GRAIN IN RAD.  *
C  *      THETCH IS THE CONTRACTION ANGLE AT THE HEAD END IN RADIANS   *
C  *****
501 FORMAT(5X,F7.3,6X,F7.3,9X,F7.3,5X,F4.0,9X,F7.5,/,7X,F7.2,7X,F6.2,9
   1X,F7.5,9X,F7.5)
   IF(Y.LE.0.0) WRITE(6,601) DO,DI,DELDI,S,THETAG,LGCI,LGNI,THETCN,TH
   TCH
601 FORMAT(20X,'C.P. GRAIN GEOMETRY',/,13X,'DO= ',F7.3,/,13X,'DI= ',F7
   1.3,/,13X,'DELDI= ',F7.3,/,13X,'S= ',F4.0,/,13X,'THETAG= ',F7.5,/,1
   23X,'LGCI= ',F7.2,/,13X,'LGNI= ',F6.2,/,13X,'THETCN= ',F7.5,/,13X,'
   3THETCH= ',F7.5,/)
   DOSQD=DO*DO
   DISQD=DI*DI
   BNUM=ANUM*DOSQD
   TLL=TL
   IF(ORDER.GE.3) TLL=0.0
   YDI=2.*Y+DI
   YDISQD=YDI*YDI
   ABSC=S*ANUM*(DOSQD-YDISQD)
   IF(ABSC.LE.0.0) ABSC=0.0
   IF(YDI.GT.CO) GO TO 100

```

TABLE IV-2. (Cont'd)

```

IF(THETAG.GT.0.08727) GO TO 101
IF(COP.EQ.0) GO TO 700
IF(COP.EQ.1) GO TO 701
IF(COP.EQ.2) GO TO 702
LGC=LGC1-(SQRT(DOSQD-DISQD)-SQRT(DOSQD-YDISQD))/2.-Y*COTAN(THETCN)
GO TO 710
702 LGC=LGC1-(SQRT(DOSQD-DISQD)-SQRT(DOSQD-YDISQD))
GO TO 710
701 LGC=LGC1-(SQRT(DOSQD-(DI+DELDI)**2)-SQRT(DOSQD-(YDI+DELDI)**2))/
1 2.-Y*COTAN(THETCH)
GO TO 710
700 LGC=LGC1-Y*(COTAN(THETCN)+COTAN(THETCH))
710 ABPC=PI*YDI*(LGC-TLL-S*Y)
ABNC=0.0
GO TO 732
101 CONTINUE
IF(COP.EQ.0.OR.COP.EQ.1) GO TO 720
ABPC=PI*YDI*(LGC1-(SQRT(DOSQD-DISQD)-SQRT(DOSQD-YDISQD)))/
1 2.-TLL-(S+TAN(THETAG/2.))*Y)
GO TO 730
720 ABPC=PI*YDI*(LGC1-Y*COTAN(THETCH)-TLL-(S+TAN(THETAG/2.))*Y)
730 IF(COP.EQ.1.OR.COP.EQ.2) GO TO 731
ABNC=PI*(LGNI-Y*COTAN(THETAG+THETCN)-Y*TAN(THETAG/2.))*((DI+
1 DELDI+Y+LGNI*SIN(THETAG)+Y*SIN(THETCN)/SIN(THETAG+THETCN))
GO TO 732
731 R3=((DI+DELDI)/2.+LGNI*SIN(THETAG))*COS(THETAG)-SIN(THETAG)*
1 SQRT((DO/2.)**2-((DI+DELDI)/2.+LGNI*SIN(THETAG))**2)
ABNC=PI*(LGNI-R3-Y*TAN(THETAG/2.))*((DI+DELDI)/2.+SQRT((DO/
1 2.))**2-(R3+Y)**2)*SIN(THETAG)+Y+(R3+Y)*COS(THETAG))
732 IF(ABPC.LE.0.0) ABPC=0.0
IF(ABNC.LE.0.0) ABNC=0.0
GO TO 5
100 ABNC=0.0
ABPC=0.0
5 APHT=ANUM*(DI+2.*RHT)**2
IF(APHT.GE.BNUM) APHT=BNUM
IF(K.LT.2) APHT1=APHT
APNT=ANUM*(DI+DELDI+2.*RNT)**2
IF(APNT.GE.BNUM) APNT=BNUM
IF(GRAIN.NE.1) GO TO 7
ABPS=0.0
ABSS=0.0
ABNS=0.0
GO TO 50
7 IF(Y.LE.0.0) READ(5,502) NS,LGSI,NP,RC,FILL,NN
C *****
C * READ IN BASIC GEOMETRY FOR STAR GRAIN (NOT REQUIRED FOR *
C * STRAIGHT C.P. GRAIN) *
```



TABLE IV-2. (Cont'd)

```

C *      NS IS THE NUMBER OF FLAT BURNING SLOT SIDES (NOT INCLUDING *
C *      THE NOZZLE END) *
C *      LGS1 IS THE INITIAL TOTAL LENGTH OF THE STAR SHAPED *
C *      PERFORATED GRAIN IN INCHES *
C *      NP IS THE NUMBER OF STAR POINTS *
C *      RC IS THE AVERAGE STAR GRAIN OUTSIDE RADIUS IN INCHES *
C *      FILL IS THE FILLET RADIUS IN INCHES *
C *      NN IS THE NUMBER OF STAR NOZZLE END BURNING SURFACES *
C *****
502 FORMAT(5X,F4.0,7X,F7.2,5X,F4.0,5X,F7.3,9X,F7.3,5X,F4.0)
    IF(Y.LE.0.0) WRITE(6,602) NS,LGS1,NP,RC,FILL,NN
602 FORMAT(20X,'BASIC STAR GEOMETRY',/,13X,'NS= ',F4.0,/,13X,'LGS1= ',
    1F7.2,/,13X,'NP= ',F4.0,/,13X,'RC= ',F7.3,/,13X,'FILL= ',F7.3,/,13X
    2,'NN= ',F4.0,/)
    PIDNP=PI/NP
    RCSQD=RC*RC
    FY=FILL+Y
    FYSQD=FY*FY
    IF(STAR.EQ.1) GO TO 20
    IF(STAR.EQ.2) GO TO 201
    IF(Y.GT.0.0) GO TO 179
    READ(5,421) TAUWW,L1,L2,ALPHA1,ALPHA2,HW
C *****
C *      READ IN GEOMETRY FOR WAGON WHEEL (NOT REQUIRED FOR STANDARD *
C *      OR TRUNCATED STAR GRAINS) *
C *      TAUWW IS THE THICKNESS OF THE PROPELLANT WEB IN INCHES *
C *      L1 AND L2 ARE THE LENGTHS OF THE TWO PARALLEL SIDES OF THE *
C *      TWO SETS OF STAR POINTS IN INCHES *
C *      ALPHA1 AND ALPHA2 ARE THE ANGLES BETWEEN THE SLANT SIDES OF *
C *      THE STAR POINTS CORRESPONDING TO L1 AND L2, RESPECTIVELY, *
C *      AND THE CENTER LINES OF THE POINTS IN RADIAN *
C *      HW IS HALF THE WIDTH OF THE STAR POINTS IN INCHES *
C *****
421 FORMAT(3(6X,F5.2),2(10X,F7.5),6X,F5.2)
    WRITE(6,422) TAUWW,L1,L2,ALPHA1,ALPHA2,HW
422 FORMAT(20X,'WAGON WHEEL GEOMETRY',/,13X,'TAUWW= ',F5.2,/,13X,
    1 'L1= ',F5.2,/,13X,'L2= ',F5.2,/,13X,'ALPHA1= ',F7.5,/,13X,
    2 'ALPHA2= ',F7.5,/,13X,'HW= ',F5.2,/)
    ALP2=ALPHA2
    XL2=L2
    LFW=RC-TAUWW-FILL
    LFSQD=LFW*LFW
    THETFW=ARCSIN((HW+FILL)/LFW)
    SLFW=LFW*SIN(THETFW)
179 KKK=0
    SG=0.0
    ENUM=(RCSQD-LFSQD-FYSQD)/(2.*LFW*FY)
    ALPHA2=ALP2

```

TABLE IV-2. (Cont'd)

```

      L2=XL2
190  YTAN=Y*TAN(ALPHA2/2.)
      COSALP=COS(ALPHA2)
      SINALP=SIN(ALPHA2)
      IF(YTAN.GT.L2) GO TO 182
      IF(FY.GT.SLFW) GO TO 181
      SGW=NP*(L2-2.*YTAN+(SLFW-FILL)/SINALP-Y*COTAN(ALPHA2)+FY*
1    (PID2+THETFW)+(LFW+FY)*(PIDNP-THETFW))
      GO TO 183
181  IF(Y.GT.TAUWW) GO TO 184
      SGW=NP*(FY*(PIDNP+ARSIN(SLFW/FY))+(PIDNP-THETFW)*LFW)
      GO TO 183
184  SGW=NP*FY*(THETFW+ARSIN(SLFW/FY)-ARCOS(ENUM))
      GO TO 183
182  YPO=-SLFW
      IF(ALPHA2.GE.PID2) GO TO 222
      Q=-FILL+L2*TAN(ALPHA2)-Y/COSALP
      XPI=(-Q*TAN(ALPHA2)-SQRT(-Q*Q+FYSQD/COSALP*COSALP))*COSALP*COSALP
      YPI=XPI*TAN(ALPHA2)+Q
      XPO=(YPO-Q)*COTAN(ALPHA2)
      GO TO 223
222  XPI=Y-L2
      YPI=-SQRT(FYSQD-XPI*XPI)
      XPO=XPI
223  FYLS=SQRT(SLFW*SLFW+XPI*XPI)
      XPIO2=(XPI-XPO)*(XPI-XPO)
      YPIO2=(YPI-YPO)*(YPI-YPO)
      IF(FY.GT.FYLS) GO TO 186
      IF(Y.GE.TAUWW) GO TO 185
      SGW=NP*(SQRT(XPIO2+YPIO2)+FY*(PID2+THETFW-ARSIN(XPI/FY))+(LFW+FY)*
1    (PIDNP-THETFW))
      GO TO 183
185  SGW=NP*(SQRT(XPIO2+YPIO2)+FY*(PID2-ARSIN(XPI/FY)-ARCOS(ENUM)))
      GO TO 183
186  IF(Y.GT.TAUWW) GO TO 187
      SGW=NP*(FY*(PIDNP+ARSIN(SLFW/FY))+(PIDNP-THETFW)*LFW)
      GO TO 183
187  SGW=NP*FY*(THETFW+ARSIN(SLFW/FY)-ARCOS(ENUM))
183  IF(SGW.LE.0.0) SGW=0.0
      IF(Y.GT.0.0) GO TO 188
      AGS2=.5*(PI*RCSQD-NP*LFW*SLFW*(COS(THETFW)-SIN(THETFW)*COTAN(ALPHA
1 2)-2.*(L2+FILL*TAN(ALPHA2/2.))/LFW)-(PI-THETFW*NP)*LFWSQD-2.*NP*F
2  ILL*(L2+SLFW/SINALP+LFW*(PIDNP-THETFW)+(PIDNP+PID2-1./SINALP)*
1  FILL/2.))
      AGS=AGS+AGS2
188  CONTINUE
      SG=SG+SGW
      IF(KKK.EQ.1) GO TO 24

```

TABLE IV-2. (Cont'd)

```

L2=L1
ALPHA2=ALPHA1
KKK=1
GO TO 190
201 IF(Y.LE.0.0) READ(5,503) RP,TAUS
C *****
C *      READ IN GEOMETRY FOR TRUNCATED STAR  (NOT REQUIRED FOR      *
C *      STANDARD STAR OR WAGON WHEEL)                                *
C *      RP IS THE INITIAL RADIUS OF THE TRUNCATION IN INCHES        *
C *      TAUS IS THE THICKNESS OF THE PROPELLANT WEB AT THE BOTTOM   *
C *      OF THE SLOTS IN INCHES                                       *
C *****
503 FORMAT(5X,F7.3,7X,F7.3)
      IF(Y.LE.0.0) WRITE(6,603) RP,TAUS
603 FORMAT(20X,'TRUNCATED STAR GEOMETRY',/,13X,'RP= ',F7.3,/,13X,'TAUS
1= ',F7.3,/)
      THETAS=PIDNP
      RPY=RP+Y
      LS=RC-TAUS-FILL-RP
      RPL=RP+LS
      THETS1=THETAS-ARSIN(FY/RPY)
      IF(THETS1.LE.0.0) GO TO 110
      IF(Y.LE.TAUS) GO TO 103
      THETAC=ARSIN((RCSQD-RPL*RPL-FYSQD)/(2.*FY*RPL))
      IF(THETAC.GE.0.0) GO TO 104
      IF(Y.LT.RC-RP) GO TO 105
      SG=0.0
      GO TO 14
103 SG=2.*NP*(RPY*THETS1+LS-(RPY*COS(THETAS-THETS1)-RP)+PID2*FY)
      GO TO 14
104 SG=2.*NP*(RPY*THETS1+LS-(RPY*COS(THETAS-THETS1)-RP)+FY*THETAC)
      GO TO 14
105 SG=2.*NP*(RPY*THETS1+SQRT(RCSQD-FYSQD)-SQRT(RPY*RPY-FYSQD))
      14 IF(Y.LE.0.0) AGS=PI*(RCSQD-RP*RP)-NP*(PI*FILL*FILL/2.+2.*LS*FILL)
      GO TO 31
110 THETAF=THETAS
      THETAP=2.*THETAS
      TAUWS=TAUS
      GO TO 111
20 IF(Y.LE.0.0) READ(5,504) THETAF,THETAP,TAUWS
C *****
C *      READ IN GEOMETRY FOR STANDARD STAR  (NOT REQUIRED FOR      *
C *      TRUNCATED STAR OR WAGON WHEEL)                                *
C *      THETAF IS THE ANGLE LOCATION OF THE FILLET CENTER IN RADIAN *
C *      THETAP IS THE ANGLE OF THE STAR POINT IN RADIAN            *
C *      TAUWS IS THE WEB THICKNESS OF THE GRAIN IN INCHES          *
C *****
504 FORMAT(9X,F7.5,9X,F7.5,8X,F6.3)

```

TABLE IV-2. (Cont'd)

```

      IF(Y.LE.0.0) WRITE(6,604) THETAF,THETAP,TAUWS
604  FORMAT(20X,'STANDARD STAR GEOMETRY',/,13X,'THETAF= ',F7.5,/,13X,'T
      HETAP= ',F7.5,/,13X,'TAUWS= ',F6.3,/)
      THETAS=PI/NP
      THETS1=1.00
111  LF=RC-TAUWS-FILL
      CNUM=(Y+FILL)/LF
      DNUM=SIN(THETAF)/SIN(THETAP/2.)
      ENUM=(RCSQD-LF*LF-FYSQD)/(2.*LF*FY)
      FNUM=SIN(THETAF)/COS(THETAP/2.)
      IF(CNUM.LE.FNUM) GO TO 106
      IF(Y.LE.TAUWS) GO TO 107
      SG=2.*NP*FY*(THETAF+ARSIN(SIN(THETAF)/CNUM)-ARCOS(ENUM))
      GO TO 23
106  IF(Y.LE.TAUWS) SG=2.*NP*LF*(DNUM+CNUM*(PID2+THETAS-THETAP/2.
      1-COTAN(THETAP/2.))+THETAS-THETAF)
      IF(Y.LE.TAUWS) GO TO 23
      SG=2.*NP*(FY*ARSIN(ENUM-(THETAS-THETAP/2.))+LF*DNUM-FY*COTAN(THETA
      1P/2.))
      GO TO 23
107  SG=2.*NP*LF*(CNUM*(THETAS+ARSIN(SIN(THETAF)/CNUM))+THETAS-THETAF)
23  IF(THETS1.LE.0.0) GO TO 14
      IF(Y.LE.0.0) AGS=PI*RC*Q2-NP*LF*LF*(SIN(THETAF)*(COS(THETAF)-
      1SIN(THETAF)*COTAN(THETAP/2.))+THETAS-THETAF+2.*FILL/LF*(SIN(THETAF
      2)/SIN(THETAP/2.))+THETAS-THETAF+FILL/(2.*LF)*(PID2+THETAS-THE
      3TAP/2.-COTAN(THETAP/2.)))
24  CONTINUE
31  IF(SG.LE.0.0) SG=0.0
      IF(K.EQ.0.OR.K.EQ.2) SGN=SG
      IF(K.LE.1) SGH=SG
      IF(Y.LE.0.0) SG2=SG
      IF(K.EQ.2) GO TO 37
      RAVEDT=R1+(SG+SG2)/2.*RBAR*DELTAT
      RNDT=R2+(SG+SG2)/2.*RNAVE*DELTAT
      RHDT=R3+(SG+SG2)/2.*RHAVE*DELTAT
      R1=RAVEDT
      R2=RNDT
      R3=RHDT
      SG2=SG
      GO TO 38
37  IF(KOUNT.NE.1) GO TO 39
      SG3=SG
      R4=R1
      R5=R2
      R6=R3
39  RAVEDT=R4+(SG+SG3)/2.*RBAR*DELTAT
      RNDT=R5+(SG+SG3)/2.*RNAVE*DELTAT
      RHDT=R6+(SG+SG3)/2.*RHAVE*DELTAT

```

TABLE IV-2. (Cont'd)

```

RHDT=R6+(SG+SG3)/2.*RHAVE*DELTAT
R4=RAVEDT
R5=RNDT
R6=RHDT
SG3=SG
38 ABSS=(AGS-RAVEDT)*NS
IF(ABSS.LE.0.0.OR.SG.LE.0.0) ABSS=0.0
ABNS=(AGS-RNDT)*NN
IF(ABNS.LE.0.0.OR.SG.LE.0.0) ABNS=0.0
IF(ORDER.LE.2) ABPS=(LGSI-Y*(NS+NN))*SG
IF(ORDER.LE.2) GO TO 36
ABPS=(LGSI-TL-Y*(NS+NN))*SG
36 PIRCRC=PI*RCSQD
APHS=PIRCRC-AGS+RHDT
IF(APHS.GE.PIRCRC.OR.SG.LE.0.0) APHS=PIRCRC
APNS=PIRCRC-AGS+RNDT
IF(K.LT.2) APHS1=APHS
IF(APNS.GE.PIRCRC) APNS=PIRCRC
50 IF(NT.EQ.0.0) GO TO 371
IF(Y.LE.0.0) READ(5,506) LTP,DTP,THETTP,TAUEFF
C *****
C * READ IN GEOMETRY ASSOCIATED WITH TERMINATION PORTS (NOT *
C * REQUIRED IF NT=0) *
C * LTP IS THE INITIAL LENGTH OF THE TERMINATION PASSAGES *
C * IN INCHES *
C * DTP IS THE INITIAL DIAMETER OF THE TERMINATION PASSAGE *
C * IN INCHES *
C * THETTP IS THE ACUTE ANGLE BETWEEN THE AXIS OF THE PASSAGE *
C * AND THE MOTOR AXIS IN RADIANS *
C * TAUEFF IS THE ESTIMATED EFFECTIVE WEB THICKNESS AT THE *
C * TERMINATION PORT IN INCHES *
C *****
506 FORMAT(7X,F6.2,7X,F5.2,10X,F7.5,10X,F6.3)
IF(Y.LE.0.0) WRITE(6,606) LTP,DTP,THETTP,TAUEFF
606 FORMAT(20X,'TERMINATION PORT GEOMETRY',/,13X,'LTP= ',F6.2,/,13X,'D
1TP= ',F5.2,/,13X,'THETTP= ',F7.5,/,13X,'TAUEFF= ',F6.3,/)
DABT=NT*3.14159*((DTP+2.*Y)*(LTP-Y/SIN(THETTP))-(DTP+2.*Y)**2/4.+
1(Y+DTP/2.)*(DTP/2.)*(1.-1./SIN(THETTP)))
IF(Y.GE.TAUEFF) DABT=0.0
371 IF(Y.GT.0.0) GO TO 52
IF(NT.NE.0.0) GO TO 45
LTP=0.0
DTP=0.0
45 IF(GRAIN.NE.2) GO TO 49
LGCI=0.0
LGNI=0.0
49 IF(GRAIN.EQ.1) LGSI=0.0
VCI=1.1*(ANUM*DISQD*(LGCI+LGNI)+(ANUM*DOSQD-AGS)*LGSI+NT*LTP*ANUM*

```

TABLE IV-2. (Cont'd)

```

1  DTP*(DTP)+VCIT
52  BBP=0.0
    BBS=0.0
    BBN=0.0
    ABPORT=ABPT+ABPC+ABPS+DABT+BBP
    ABSLOT=ABST+ABSC+ABSS+BBS
    ABNOZ=ABNT+ABNC+ABNS+BBN
    SUMAB=ABPORT+ABSLOT+ABNOZ
    IF(K.EQ.0) GO TO 99
    IF(K.EQ.1) ABMAIN=ABPORT+ABSLOT+ABNOZ
    K=K+1
    IF(K.GT.2) GO TO 69
    GO TO 2
69  ABTO=ABPORT+ABSLOT+ABNOZ
99  CONTINUE
    IF(Y.GT.0.0) GO TO 70
    ABP1=ABPORT
    ABN1=ABNOZ
    ABS1=ABSLOT
70  ABP2=(ABP1+ABPORT)/2.
    ABN2=(ABN1+ABNOZ)/2.
    ABS2=(ABS1+ABSLOT)/2.
    IF(INPUT.EQ.1) GO TO 76
    GO TO (71,72,73,74),ORDER
71  APHEAD=APHS1
    APNOZ=APNT
    SG=SGH
    GO TO 75
72  APHEAD=APHT1
    APNOZ=APNT
    SG=0.0
    IF(GRAIN.EQ.3) SG=(SGH+SGN)/2.
    GO TO 75
73  APHEAD=APHT1
    APNOZ=APNS
    SG=SGN
    GO TO 75
74  APHEAD=APHS1
    APNOZ=APNS
    SG=SGN
    GO TO 75
76  APHEAD=APHT
    APNOZ=APNT
75  Y=YB
    DIFF=SUMAB-SUM2
    DADY=DIFF/DELY
    ABP1=ABPORT
    ABN1=ABNOZ

```

TABLE IV-2. (Cont'd)

```
ABSI=ABSLOT  
IF(ZW.GE.0.0) GO TO 77  
ABM1=ABMAIN  
ABMAIN=ABTO  
ABTO=ABM1  
77 RETURN  
END
```

TABLE IV-2. (Cont'd)

## SUBROUTINE OUTPUT

```

C *****
C * SUBROUTINE OUTPUT CALCULATES BASIC PERFORMANCE PARAMETERS *
C * AND PRINTS THEM OUT *
C * (WEIGHT CALCULATIONS ARE PERFORMED IN THE MAIN PROGRAM) *
C * T IS THE TIME IN SECS *
C * Y IS THE DISTANCE BURNED IN INCHES *
C * RNOZ IS THE NOZZLE END BURNING RATE IN INCHES/SEC *
C * RHEAD IS THE HEAD END BURNING RATE IN INCHES/SEC *
C * PONOZ IS THE STAGNATION PRESSURE AT THE NOZZLE END IN PSIA *
C * PHEAD IS THE PRESSURE AT THE HEAD END OF THE GRAIN IN PSIA *
C * PTAR IS THE PORT TO THROAT AREA RATIO *
C * MNOZ IS THE MACH NUMBER AT THE NOZZLE END OF THE GRAIN *
C * PATM IS THE ATMOSPHERIC PRESSURE AT ALTITUDE IN PSIA *
C * SUMAB IS THE TOTAL BURNING AREA OF PROPELLANT IN IN**2 *
C * SG IS THE BURNING PERIMETER IN INCHES OF THE STAR SEGMENT *
C * (IF ANY) *
C * CFVAC IS THE VACUUM THRUST COEFFICIENT *
C * FVAC IS THE VACUUM THRUST IN LBS *
C * F IS THE THRUST IN LBS *
C *****
C REAL MGEN,MDIS,MNOZ,MN1,JROCK,N,L,ME1,ME,ISP,ITOT,MU,MASS,ISPVAC
C REAL M2,MDBAR,ISP2,ITVAC
C COMMON/CONST1/ZW,AE,AT,THETA,ALFAN
C COMMON/CONST2/CAPGAM,ME,BOT,ZETAF,TB,HB,GAM
C COMMON/VAR1A1/Y,T,DELY,DELTAT,PONOZ,PHEAD,RNOZ,RHEAD,SUMAB,PHMAX
C COMMON/VAR1A3/ITOT,ITVAC,JROCK,ISP,ISPVAC,MDIS,MNOZ,SG,SUMMT
C COMMON/VAR1A5/ABMAIN,ABTO,SUMDY,VC1,VC
C COMMON/PLOTT/NUMPLT(16),IPO,NDUM,NP,IOP
C DIMENSION TPLOT(200),PNPLOT(200),PHPLOT(200),FPLOT(200),
1 FVPLOT(200),RNPLOT(200),RHPLOT(200),YBPLOT(200),ABPLOT(200),
1 SGPLOT(200),VCPLOT(200)
C DATA G/32.1725/
C IF(NDUM.EQ.1) GO TO 2
C NP=NP+1
C YB=Y
C IF(Y.LE.0.0) M2=MDIS
C MDBAR=(M2+MDIS)/2.
C SUMMT=SUMMT+MDBAR*DELTAT
C PTAR=1./JROCK
C PRES=(1.+BOT/2.*ME*ME)**(-GAM/BOT)
C ALT=HB*(T/TB)**(7./3.)
C PATM=14.696/EXP(0.43103E-04*ALT)
C IF(MDIS.LE.0.0.OR.PONOZ.LE.0.0) GO TO 45
C CF=CAPGAM*SQRT(2.*GAM/BOT*(1.-PRES**((BOT/GAM)))+AE/AT*(PRES-PATM/P
1 ONOZ)
C CFVAC=CF+AE/AT*PATM/PONOZ
C F=ZETAF*COS(THETA)*PONOZ*AT*((1.+COS(ALFAN))/2.*CF+(1.-COS(ALFAN))

```



TABLE IV-2. (Cont'd)

```

1/2.*AE/AT*(PRES-PATM/PONQZ))
  IF(F.LE.0.0) F=0.0
  IF(Y.LE.0.0) F2=F
  FBAR=(F+F2)/2.
  FVAC=ZETA*F*COS(THETA)*PONQZ*AT*((1.+COS(ALFAN))/2.*CFVAC+(1.-COS(
1LFAN))/2.*AE/AT*PRES)
  IF(Y.LE.0.0) FV2=FVAC
  FVBAR=(FV2+FVAC)/2.
  ISP=F/(MDIS*G)
  ISPVAC=FVAC/(MDIS*G)
  ITOT=ITOT+FBAR*DELTAT
  ITVAC=ITVAC+FVBAR*DELTAT
  M2=MDIS
  F2=F
  FV2=FVAC
  IF(PHEAD.GT.PHMAX) PHMAX=PHEAD
  GO TO 47
45 CFVAC=0.0
  FVAC=0.0
  F=0.0
47 WRITE(6,1) T,YB,RNOZ,RHEAD,PONQZ,PHEAD,PTAR,MNOZ,SUMAB,SG,PATM,CFV
  1AC,FVAC,F
1 FORMAT(/,13X,'TIME= ',F7.3,12X,'Y= ',F6.3,/,13X,'RNOZ= ',1PE11.4,
1' RHEAD= ',1PE11.4,' PONQZ= ',1PE11.4,' PHEAD= ',1PE11.4,/,13X,
2'PTAR= ',1PE11.4,' MNOZ= ',1PE11.4,' SUMAB= ',1PE11.4,' SG=
3 ',1PE11.4,/,13X,'PATM= ',1PE11.4,' CFVAC= ',1PE11.4,' FVAC= ',
41PE11.4,' F= ',1PE11.4)
  IF(IPO.EQ.0) RETURN
  TPLT(NP)=T
  PNPLT(NP)=PONQZ
  PHPLT(NP)=PHEAD
  FPLT(NP)=F
  FVPLT(NP)=FVAC
  RNPLT(NP)=RNOZ
  RHPLT(NP)=RHEAD
  YBPLT(NP)=YB
  ABPLT(NP)=SUMAB
  SGPLT(NP)=SG
  VCPLT(NP)=VC
  RETURN
2 NP=NP+2
  IOP=1
  DO 1004 I=1,16
  IF(NUMPLT(I).EQ.1) GO TO 1003
  GO TO 1004
1003 GO TO (10,20,30,40,50,55,60,70,75,80,90,95,97,100,110,115),I
10 CALL PLOTIT(TPLT,'TIME (SECS)',11,PHPLT,'PHEAD (PSIA)',12,
1 PNPLT,'PONQZ',5,NP,1,'DUMMY',5)

```

TABLE IV-2. (Cont'd)

```

▶ GO TO 1004
▶ 20 CALL PLOTIT(TPLOT,'TIME (SECS)',11,PNPLOT,'PONOZ (PSIA)',12,PHPLOT
▶ 1,'PHEAD (PSIA)',12,NP,1,'DUMMY',5)
▶ GO TO 1004
▶ 30 CALL PLOTIT(TPLOT,'TIME (SECS)',11,PHPLOT,'PHEAD',5,PNPLOT
▶ 1,'PONOZ',5,NP,3,'PRESSURE (PSIA)',15)
▶ GO TO 1004
▶ 40 CALL PLOTIT(TPLOT,'TIME (SECS)',11,RHPLOT,'RHEAD (IN PER SEC)',18,
▶ 1PHPLOT,'PHEAD (PSIA)',12,NP,1,'DUMMY',5)
▶ GO TO 1004
▶ 50 CALL PLOTIT(TPLOT,'TIME (SECS)',11,RNPLOT,'RNOZ (IN PER SEC)',17,
▶ 1PNPLOT,'PONOZ (PSIA)',12,NP,1,'DUMMY',5)
▶ GO TO 1004
▶ 55 CALL PLOTIT(TPLOT,'TIME (SECS)',11,RHPLOT,'RHEAD',5,RNPLOT,
▶ 1 'RNOZ',4,NP,3,'BURNING RATE (IN PER SEC)',25)
▶ GO TO 1004
▶ 60 CALL PLOTIT(TPLOT,'TIME (SECS)',11,ABPLOT,'TOTAL BURNING AREA (SQ
▶ 1IN)',26,PNPLOT,'PONOZ',5,NP,1,'DUMMY',5)
▶ GO TO 1004
▶ 70 CALL PLOTIT(TPLOT,'TIME (SECS)',11,SGPLOT,'STAR PERIMETER (IN)',19
▶ 1,PNPLOT,'PONOZ',5,NP,1,'DUMMY',5)
▶ GO TO 1004
▶ 75 CALL PLOTIT(TPLOT,'TIME (SECS)',11,ABPLOT,'TOTAL BURNING AREA (SQ
▶ 1IN)',26,SGPLOT,'STAR PERIMETER (IN)',19,NP,2,'DUMMY',5)
▶ GO TO 1004
▶ 80 CALL PLOTIT(TPLOT,'TIME (SECS)',11,FPLOT,'THRUST (LBS)',12,PNPLOT,
▶ 1'PONOZ',5,NP,1,'DUMMY',5)
▶ GO TO 1004
▶ 90 CALL PLOTIT(TPLOT,'TIME (SECS)',11,FVLOT,'VACUUM THRUST (LBS)',19
▶ 1,PNPLOT,'PONOZ',5,NP,1,'DUMMY',5)
▶ GO TO 1004
▶ 95 CALL PLOTIT(TPLOT,'TIME (SECS)',11,FPLOT,'THRUST',6,FVLOT,
▶ 1 'VACUUM THRUST',13,NP,3,'THRUST (LBS)',12)
▶ GO TO 1004
▶ 97 CALL PLOTIT(TPLOT,'TIME (SECS)',11,VCLOT,'CHAMBER VOLUME (IN**3)'
▶ 1 ,22,PNPLOT,'PONOZ',5,NP,1,'DUMMY',5)
▶ GO TO 1004
▶ 100 CALL PLOTIT(YBLOT,'BURNED DISTANCE (IN)',20,ABPLOT,'TOTAL BURNING
▶ 1 AREA (SQ IN)',26,PNPLOT,'PONOZ',5,NP,1,'DUMMY',5)
▶ GO TO 1004
▶ 110 CALL PLOTIT(YBLOT,'BURNED DISTANCE (IN)',20,SGPLOT,'STAR PERIMETE
▶ 1R (IN)',19,PNPLOT,'PONOZ',5,NP,1,'DUMMY',5)
▶ GO TO 1004
▶ 115 CALL PLOTIT(YBLOT,'BURNED DISTANCE (IN)',20,ABPLOT,'TOTAL BURNING
▶ 1 AREA (SQ IN)',26,SGPLOT,'STAR PERIMETER (IN)',19,NP,2,'DUMMY',5)
▶ 1004 CONTINUE
▶ RETURN
▶ END

```

TABLE IV-2. (Cont'd)

```

SUBROUTINE IGNITN
C *****
C * SUBROUTINE IGNITN CALCULATES THE PRESSURE RISE DURING *
C * THE IGNITION PERIOD *
C * ASIG IS THE IGNITER THROAT AREA IN IN**2 *
C * WIGTOT IS THE TOTAL WEIGHT OF THE IGNITER IN LBS *
C * MIGAV IS THE IGNITER AVERAGE MASS FLOW RATE IN SL/SEC *
C * PCIG IS THE IGNITER PRESSURE IN LBS/IN**2 *
C *****
COMMON/CONST1/ZW,AE,AT,THETA,ALFAN
COMMON/CONST2/GAMMA,ME,BOT,ZETAF,TB,HB,GAM
COMMON/VAR1A1/Y,TIG,DELY,DELTAT,PONQZ,PHEAD,RNOZ,RHEAD,SUMAB,PHMAX
COMMON/VAR1A2/ABPORT,ABSLOT,ABNOZ,APHEAD,APNOZ,DADY,ABP2,ABN2,ABS2
COMMON/VAR1A3/ITOT,ITVAC,JROCK,ISP,ISPVAC,MDIS,MNOZ,SG,SUMMT
COMMON/VAR1A5/ABMAIN,ABTO,SUMDY,VC,VC
COMMON/IGN1/KA,KB,UFS,RHO,A,XN,L,PMIG,TI1,TI2,CSIG
COMMON/IGN2/ALPHA,BETA,PBIG,RRIG,DELTIG,X,TOP,ZAP
COMMON/PLOTT/NUMPLT(16),IPO,NDUM,IPT,IOP
DIMENSION B(9)
REAL K(4),L,KA,KB,JROCK,J2,MIG,MIGAV,MSRM,ME,MDIS,MNOZ,MNOZI,MN1
DATA A1,A2,A3,A4/.17476,-.551481,1.205536,.171185/
DATA B(1),B(2),B(3),B(4),B(5)/0.,.4,.455737,1.,.296978/
DATA B(6),B(7),B(8),B(9)/.15876,.2181,-3.050965,3.832864/
C *****
C * THE A'S AND B'S ARE CONSTANTS FOR THE RUNGE-KUTTA INTEGRATION *
C *****
DATA G/32.1725/
XXX=.05*PONQZ
IPLUG=0
PONQZI=PONQZ
RHEADI=RHEAD
RNOZI=RNOZ
PHEADI=PHEAD
DELTIT=DELTAT
DISM=MDIS
DELTAT=DELTIG
SUMABI=SUMAB
MNOZI=MNOZ
MNOZ=0.0
RHEAD=0.0
RNOZ=0.0
MDIS=0.0
ABI=0.0
TIGI=C.0
PCI=14.696
TIG=0.0
PCNEW=14.696
SUMAB=0.0

```

TABLE IV-2. (Cont'd)

```

PCIG=14.696
PHEAD=14.696
PNOZ=14.696
SLOPE=SUMABI/L
G2=GAMMA*GAMMA
J2=JROCK*JROCK
GJ=G2*J2/2.
MIGAV=.2*AT/G
ASIG=4.*MIGAV*CSIG/(4.*PMIG-RRIG*(TI2-TI1))
WIGTOT=G*MIGAV*(5.*(TI2-TI1)/6.)
WRITE(6,999) ASIG,WIGTOT,MIGAV
999 FORMAT(///,20X,'IGNITER SIZE CALCULATIONS',/,13X,'ASIG=',F6.2,/,
1 13X,'WIGTOT=',F7.2,/,13X,'MIGAV=',F8.3,///)
WRITE(6,10)
10 FORMAT(33X,'*****',/,33X,'**** IGNITION TRA
INSIENT ****',/,33X,'*****')
18 NNN=0
CALL OUTPUT
WRITE(6,30) PCIG
30 FORMAT(13X,'PCIG= ',1PE11.4)
9 CONTINUE
DO 8 N=1,4
IF(N.EQ.1) PC=PCI
IF(N.EQ.2) PC=PCI+B(2)*K(1)
IF(N.EQ.3) PC=PCI+B(5)*K(1)+B(6)*K(2)
IF(N.EQ.4) PC=PCI+B(7)*K(1)+B(8)*K(2)+B(9)*K(3)
TIG=TIGI+B(N)*DELTIG
SUMAB=ABI+SLOPE*UFS*B(N)*DELTIG
IF(SUMAB.GT.SUMABI) SUMAB=SUMABI
PHEAD=PC
IF(MDIS.NE.0.0) PHEAD=PC*(1.+GJ)
RHEAD=A*PHEAD**XN
IF(TIG.LE.TI1) PCIG=PMIG*TIG/TI1
IF(TIG.GT.TI1.AND.PCIG.GT.PHEAD) PCIG=PMIG-RRIG*(TIG-TI1)
IF(PCIG.LE.PHEAD) PCIG=PHEAD
MIG=0.0
IF(PCIG.GT.PHEAD.AND.TIG.LE.TI2/2.) MIG=PCIG*ASIG/CSIG
CSTR=KA+KB*PC
MDIS=PC*AT/CSTR
IF(PC.LE.PBIG.AND.IPLUG.EQ.0) GO TO 7
IPLUG=1
MNOZ=MNOZI
PNOZ=PC*(1.-GJ)
ZIT=MDIS*X/APNOZ
RN1=RHEAD
AZ=ALPHA*ZIT**.8
XL=UFS*TIG
IF(XL.GT.L) XL=L

```

TABLE IV-2. (Cont'd)

```

4 EX=XL**.2*EXP(BETA*RN1*RHO/ZIT)
  RNOZ=RN1-(RN1-A*PNOZ**XN-AZ/EX)/(1.+AZ*BETA*RHO/(ZIT*EX))
  IF(ABS(RN1-RNOZ).LE.0.002) GO TO 5
  RN1=RNOZ
  GO TO 4
7 MDIS=0.0
  MNOZ=0.0
  PNOZ=PC
  RNOZ=RHEAD
5 CONTINUE
  MSRM=RHO*SUMAB*(RNOZ+RHEAD)/2.
  DENOM=(VCI/(12.*CSTR*CSTR*G2))*(1.-(2.*KB*PC)/CSTR)
  DPDT=(MIG+MSRM-MDIS)/DENOM
  IF(DPDT.LT.0.0.AND.PC.LT.20.0) DPDT=0.0
  K(N)=DELTIG*DPDT
8 CONTINUE
  PCNEW=PCI+A1*K(1)+A2*K(2)+A3*K(3)+A4*K(4)
  PHEAD=PCNEW
  IF(MDIS.GT.0.0) PHEAD=PCNEW*(1.+GJ)
  PCNOZ=PCNEW
  XXY=ABS(PONOI-PONOZI)
  IF(PCNEW.LE.1.001*PCI.AND.SUMAB.EQ.SUMABI.AND.XXY.LE.XXX) GO TO 13
  ABI=SUMAB
  TIGI=TIG
  PCI=PCNEW
  NNN=NNN+1
  IF(NNN.GE.5) GO TO 18
  GO TO 9
13 CONTINUE
  CALL OUTPUT
  WRITE(6,30) PCIG
  DELTAT=DELT
  MDIS=DISM
  SUMAB=SUMABI
  PNOZ=PONOZI
  RHEAD=RHEAD1
  RNOZ=RNOZI
  PHEAD=PHEAD1
  MNOZ=MNOZI
  IF(IPO.NE.2.AND.IPO.NE.3) GO TO 53
  NDUM=1
  CALL OUTPUT
  NDUM=0
53 CONTINUE
  IPT=0
  RETURN
  END

```

TABLE IV-2. (Cont'd)

```

SUBROUTINE PLOTIT(X,XHDR,KX,Y,YHDR,NY,T,THDR,NT,NP,NPLOT,DUMMY,ND)
*****
* SUBROUTINE PLOTIT PLOTS TWO DEPENDENT VARIABLES, Y AND T, *
* VERSUS AN INDEPENDENT VARIABLE, X *
* XHDR, YHDR, AND THDR ARE THE HEADINGS FOR THE X, Y, AND T *
* AXES, RESPECTIVELY *
* KX, NY, AND NT ARE THE NUMBER OF CHARACTERS IN THE X, Y, AND *
* T AXES HEADINGS, RESPECTIVELY (MAX OF 32 IN EACH) *
* NP IS THE NUMBER OF POINTS TO BE PLOTTED PLUS 2 *
* VALUES FOR NPLOT ARE *
* 1 FOR Y ONLY PLOTTED VERSUS X *
* 2 FOR Y AND T PLOTTED VERSUS X ON SAME AXES *
* WITH INDIVIDUAL SCALES *
* 3 FOR Y AND T PLOTTED VERSUS X ON SAME AXES *
* WITH SAME SCALES *
* DUMMY IS THE HEADING FOR THE DOUBLE AXIS (NPLOT=3) *
* ND IS THE NUMBER OF CHARACTERS IN DUMMY *
*****
DIMENSION XHDR(8),YHDR(8),THDR(8),DUMMY(8),X(NP),Y(NP),T(NP)
CALL GSIZE (12.0,11.0,1121)
NX=-KX
NM=NP-1
NN=NP-2
IF(NPLOT.EQ.1) GO TO 9
CALL SCALE(T,4.,NM,1)
9 CALL SCALE(X,8.,NN,1)
CALL SCALE(Y,4.,NN,1)
CALL PLOT(6.25,2.,-3)
IF(NPLOT.NE.3) CALL AXIS(0.,0.,YHDR,NY,4.,180.,Y(NM),Y(NP))
IF(NPLOT.EQ.3) CALL AXIS(0.,0.,DUMMY,ND,4.,180.,Y(NM),Y(NP))
CALL AXIS(0.,0.,XHDR,NX,8.,90.,X(NM),X(NP))
IF(NPLOT.EQ.1) GO TO 12
DO 11 I=1,NN
11 T(I)=-T(I)
12 DO 13 I=1,NN
13 Y(I)=-Y(I)
CALL LINE(Y,X,NN,1,1,1)
CALL PLOT(0.,0.,3)
IF(NPLOT.EQ.1) GO TO 24
IF(NPLOT.EQ.2) CALL PLOT(0.,-.5,2)
IF(NPLOT.EQ.2) CALL AXIS(0.,-.5,THDR,NT,4.,180.,T(NM),T(NP))
CALL LINE(T,X,NN,1,1,2)
DO 25 I=1,NN
25 T(I)=-T(I)
24 DO 26 I=1,NN
26 Y(I)=-Y(I)
IF(NPLOT.EQ.1) GO TO 32
CALL SYMBOL(-4.35,.52,.1,1,0.,0)

```

TABLE IV-2. (Cont'd)

```
▼ CALL SYMBOL(-4.2,.52,.1,2,0.,0)
▼ CALL SYMBOL(-4.3,.65,.1,YHDR,90.,NY)
▼ CALL SYMBOL(-4.15,.65,.1,THDR,90.,NT)
▼ 32 CALL PLOT(8.5,0.,-3)
▼ RETURN
▼ END
```

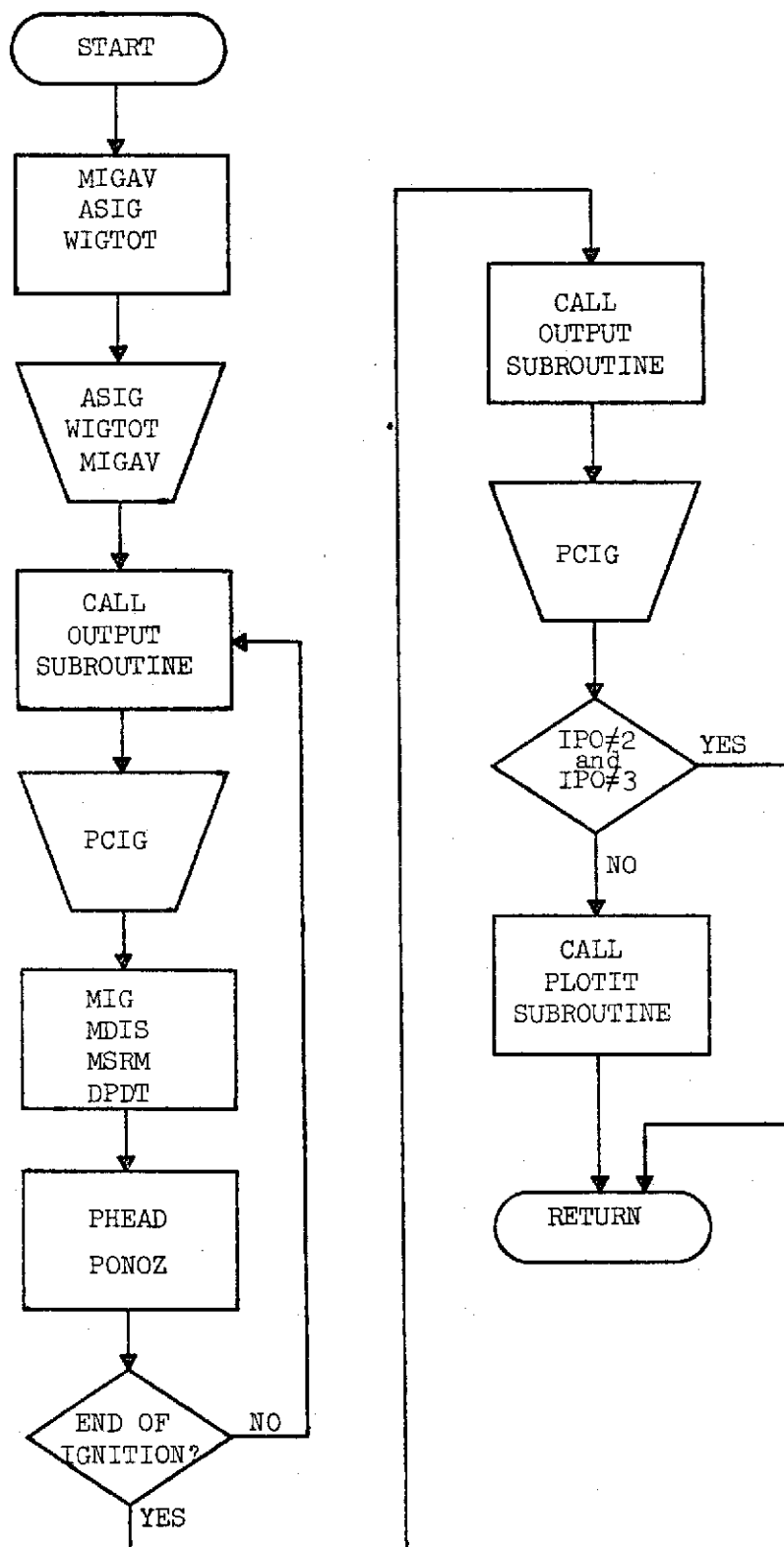


Figure IV-4. Flowchart for ignition subroutine.



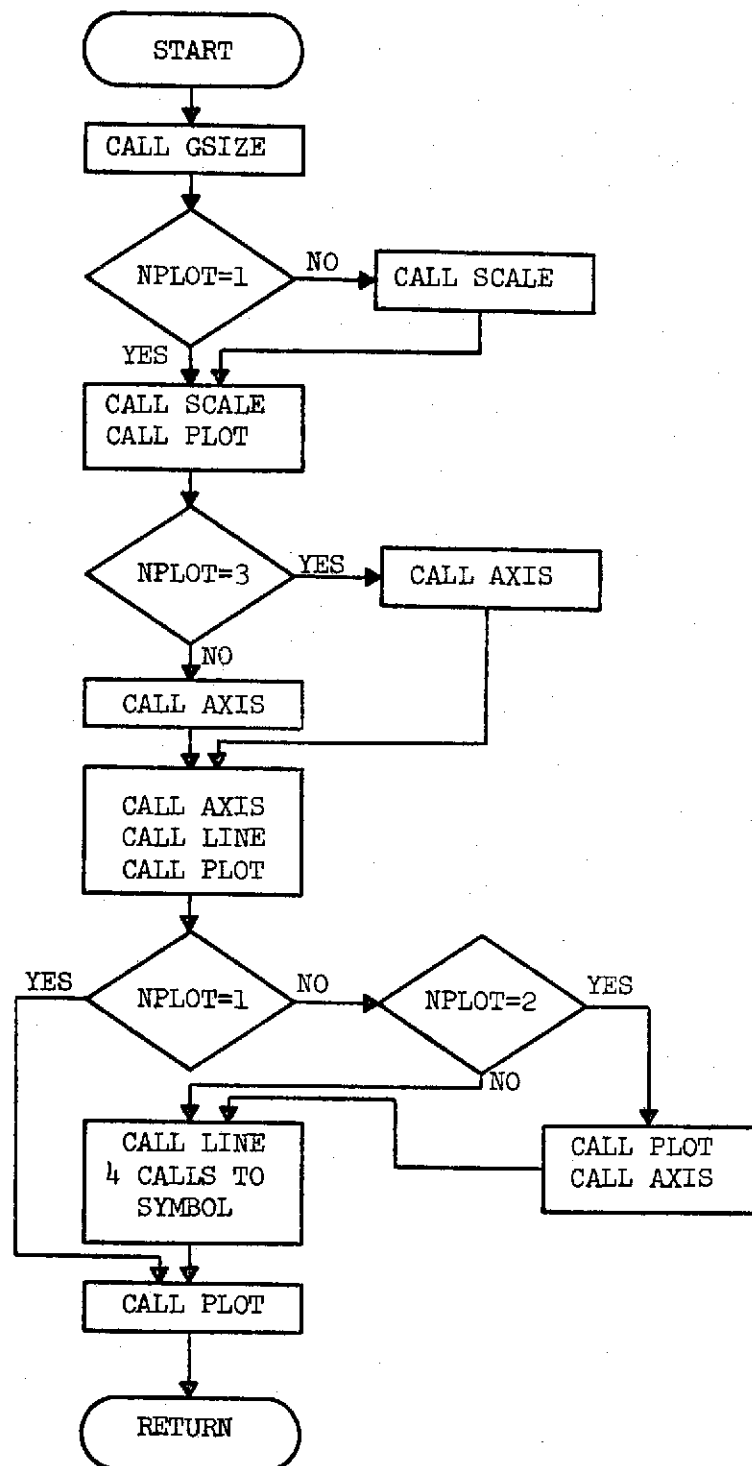


Figure IV-5. Flowchart for plotting subroutine.

## V. TEST CASES

In this section two test cases of the extended computer program are presented. Complete input data for one test case and samples of the output data for both cases demonstrating the extended capabilities of the program are presented.

### Test Case 1 - Modified SRM 1

The SRM represented in this case is the same as SRM 1 of the original report (Reference 1, Figure V-1) except that the forward segment, a truncated star grain, was replaced by a wagon wheel grain defined in the table of input data (Table V-1, present report). Figure V-1 demonstrates results of the ignition transients calculations for this SRM in the form of the actual plot obtained from the CalComp 663 digital plotter and Table V-2 shows a sample of the associated numerical printout. Plotter output of additional results are given in Figures V-2 and V-3.

### Test Case 2 - SRM 2

The SRM represented in this case is identical with SRM 2 of the original report (See Reference 1, Figure V-3 and Table V-4). However, to examine the new program capabilities, the performance of SRM 2 was calculated in two different ways: 1) with the head end of the grain considered conical ( $COP=0$ ), and 2) with the head end considered hemispherical, the more accurate geometric representation, ( $COP=3$ ). The aft end in both cases was considered flat because the propellant downstream of the aft slot is not represented by equations but by tabular values. The results for the two cases are shown on Figure V-4 and compared with static test results. It is notable that the two program results are significantly different. The hemispherical end representation gives a somewhat higher pressure level throughout equilibrium burning as would be expected from the nature of the geometric representations. (In retrospect a higher value of THETCH should have been chosen for the conical end approximation)

Although the hemispherical end approximation yields results that are better than the conical end approximation for the first two-thirds of the trace, results for the last third are the opposite. Additional investigation using the computer program indicate that the departures from test results could possibly be the result of a generally high nozzle throat erosion rate (RADER) during the particular test than that used for the program computation.

## OPTIONS

ALL OTHER A'S ARE 0.

TABLE V-2. SAMPLE PRINTOUT OF IGNITION COMPUTATIONS FOR MODIFIED SRM 1.

IGNITER SIZE CALCULATIONS  
 ASIG= 52.95  
 WIGTOT= 404.82  
 MIGAV= 10.785

\*\*\*\*\*  
 \*\*\*\* IGNITION TRANSIENT \*\*\*\*  
 \*\*\*\*\*

TIME=	C.0	Y=	C.0				
RNOZ=	0.0	RHEAD=	0.0	PONoz=	1.4696E 01	PHEAD=	1.4696E 01
PTAR=	1.3201E 00	MNOZ=	0.0	SUMAB=	0.0	SG=	7.8331E 02
PATM=	1.4696E 01	CFVAC=	0.0	FVAC=	0.0	F=	0.0
PCIG=	1.4696E 01						

TIME=	0.025	Y=	C.0				
RNOZ=	1.4143E-01	RHEAD=	1.4595E-01	PONoz=	1.7610E 01	PHEAD=	1.9662E 01
PTAR=	1.3201E 00	MNOZ=	5.2199E-01	SUMAB=	4.3135E 04	SG=	7.8331E 02
PATM=	1.4696E 01	CFVAC=	1.7775E 00	FVAC=	5.2107E 04	F=	0.0
PCIG=	4.0000E 02						

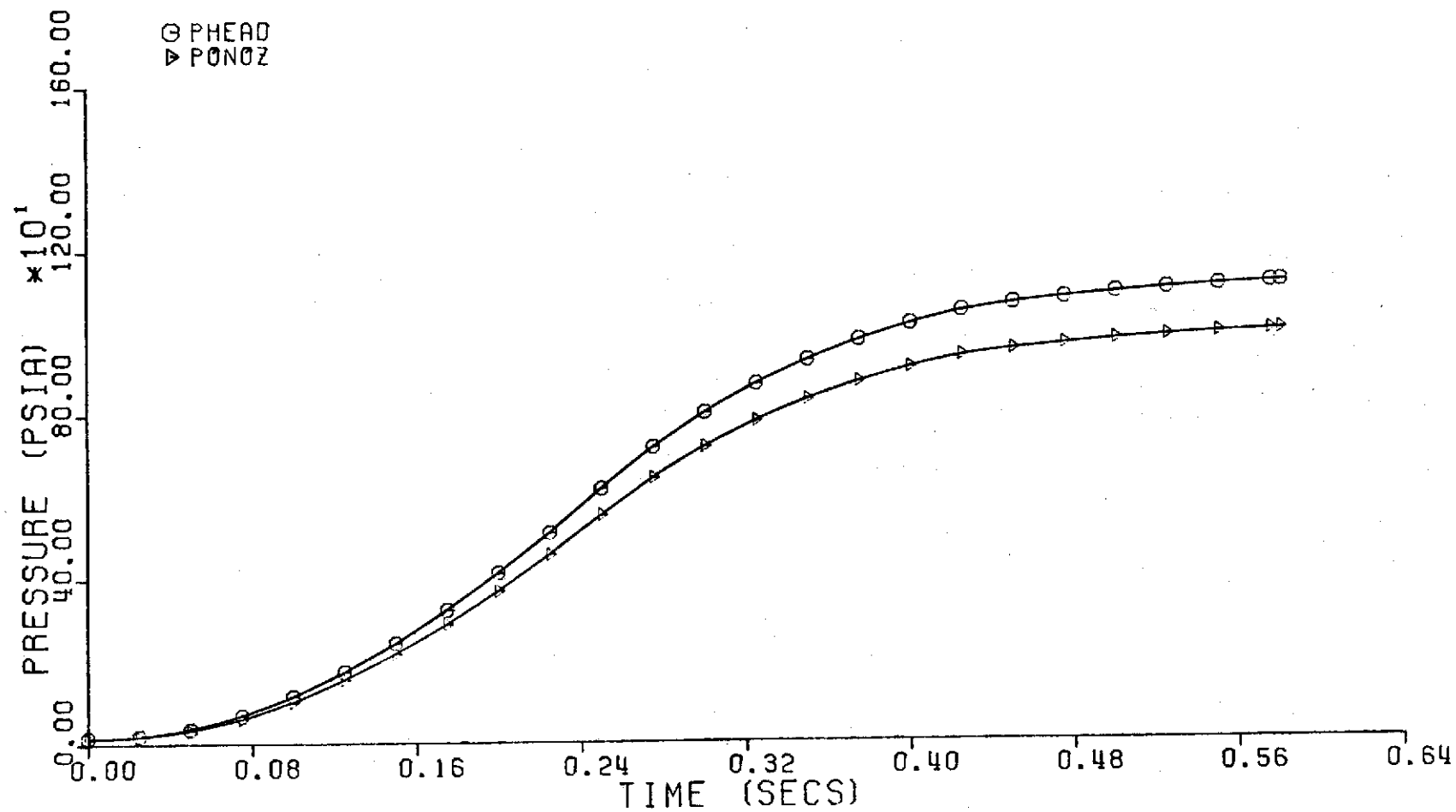


Figure V-1. Ignition transients for SRM 1 with wagon-wheel in place of truncated star grain segment.

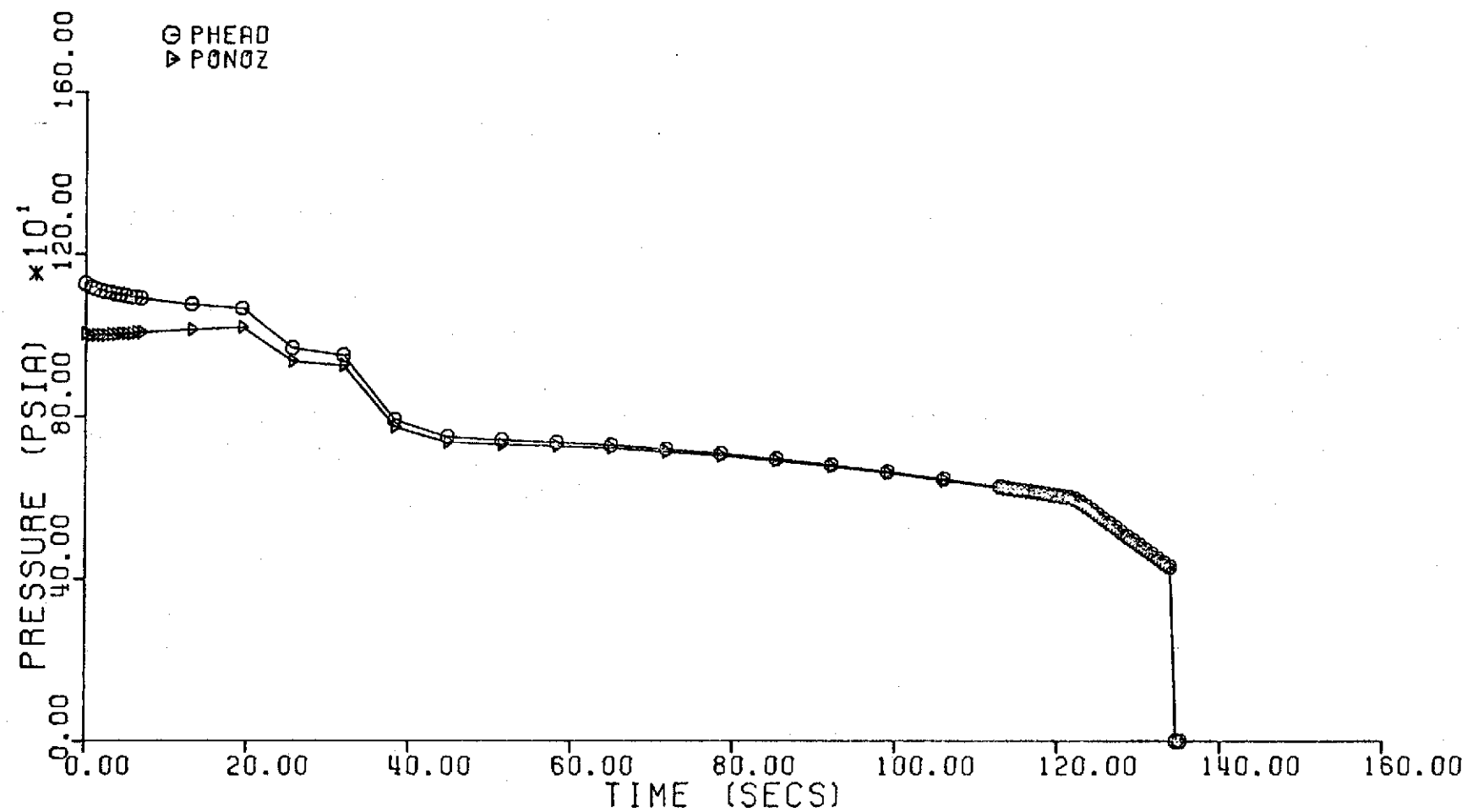


Figure V-2. Equilibrium burning and tail-off for SRM 1 with wagon-wheel in place of truncated star grain segment.

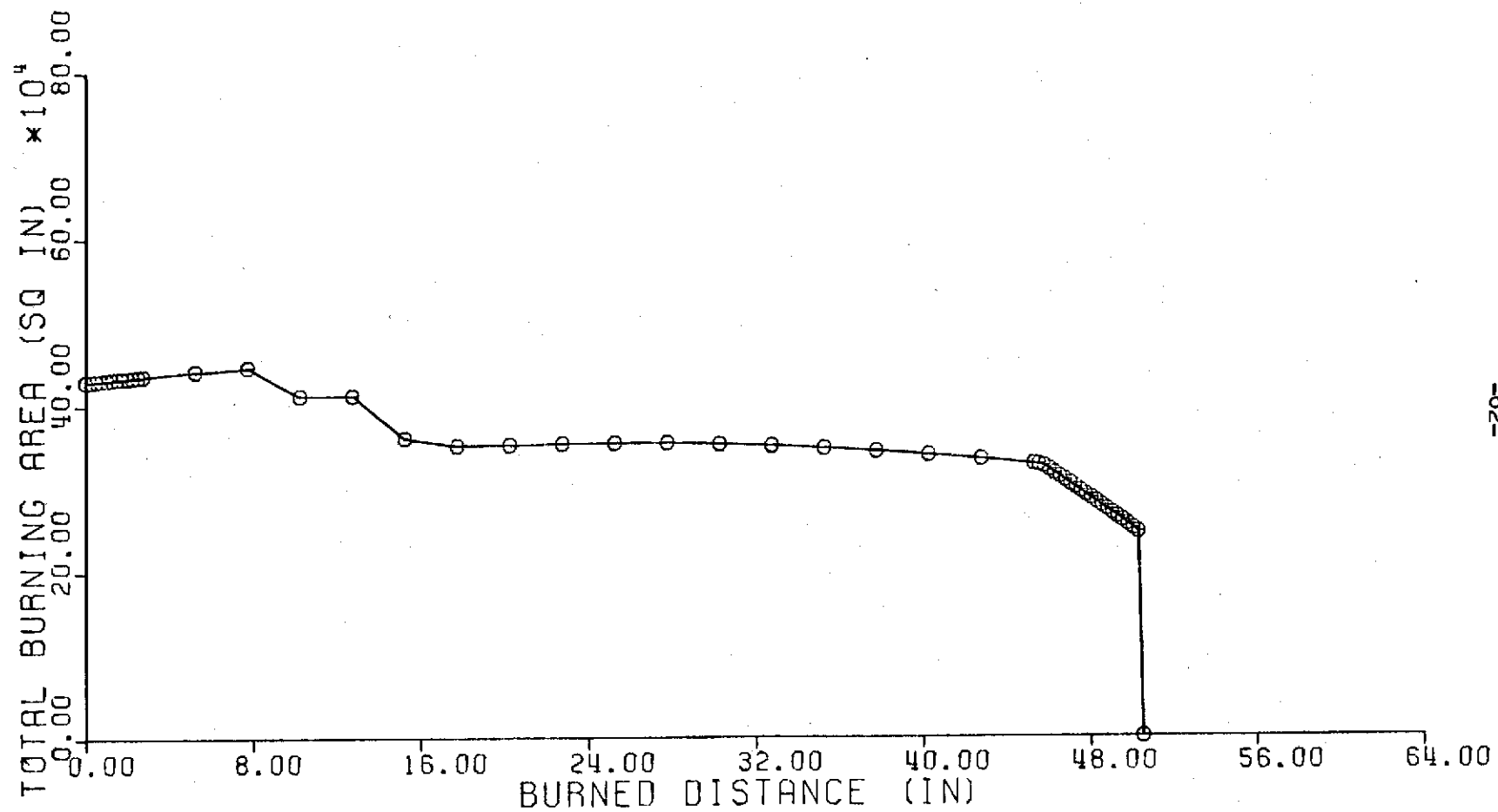


Figure V-3. Burning surface area vs. distance burned for SRM 1 with wagon-wheel in place of truncated star grain segment.

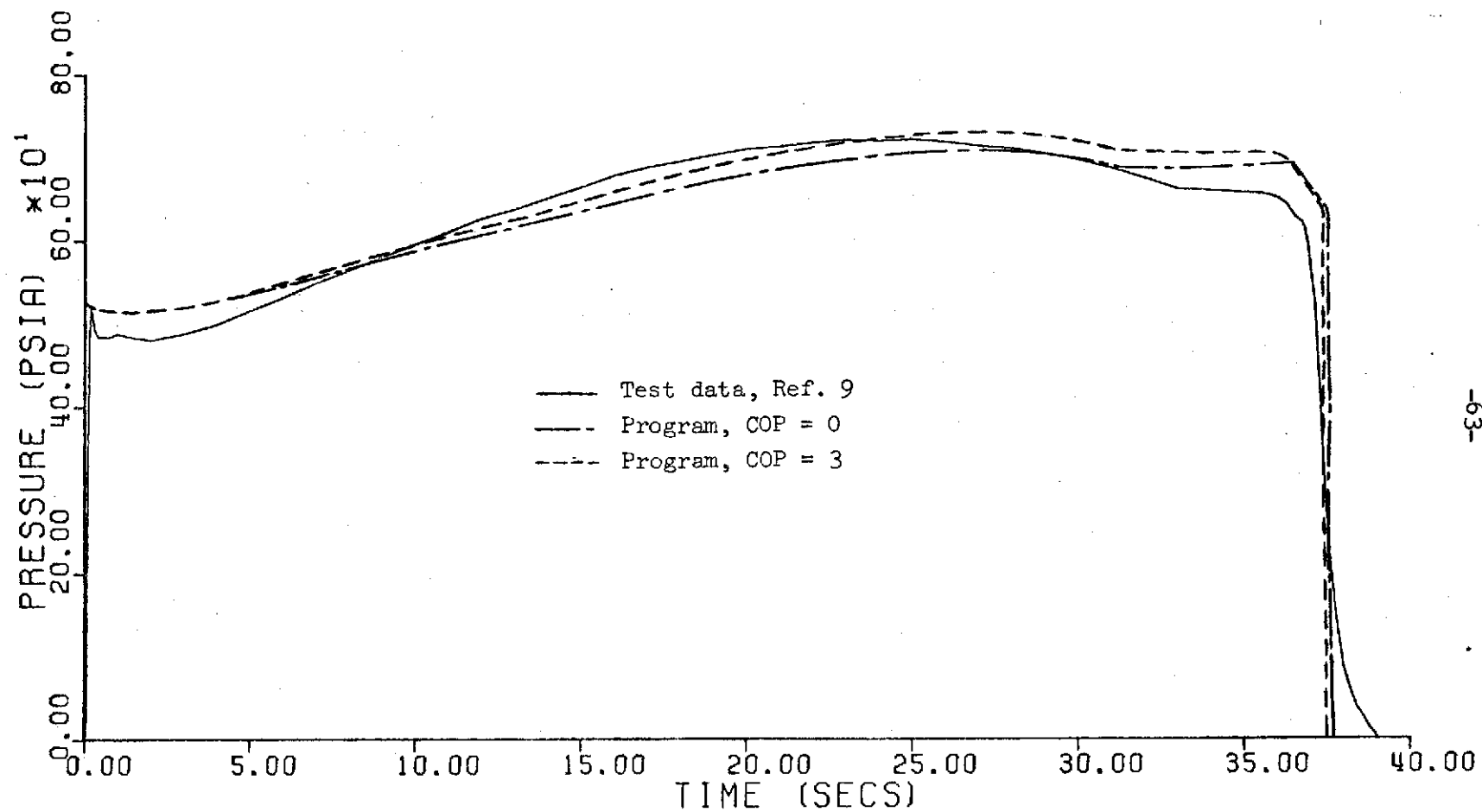


Figure V-4. Comparison of test results for SRM 2 with computer results obtained using various methods of representing head end grain geometry.



## VI. CONCLUDING REMARKS

The extended SRM design and analysis program presented in this report considerably improves the capability of the program by permitting calculation of ignition transients and wagon-wheel type grain configurations. The plotting option offers an aid to the designer for rapid interpretation of the results.

A number of changes in the program, notable among which are calculation of initial and final gaseous chamber volume and more accurate geometric representation of the ends of circular-perforated grains should result in somewhat more accurate SRM performance predictions. Additional refinements are of course possible, but, as in the present case, the refinements will add to the complexity of the input preparation and the computer operating time. Before incorporating such changes, the degree of improvement in prediction capability anticipated should be evaluated in light of the basic objective of the present work of providing a simplified program and in light of the approximations inherent in the internal ballistics model used.

#### REFERENCES

1. Sforzini, R. H., "Design and Performance Analysis of Solid-Propellant Rocket Motors Using a Simplified Computer Program," Final Report, prepared for NASA, Auburn University, October 1972.
2. Sforzini, R. H., and Fellows, H. L., Jr., "Prediction of Ignition Transients in Solid-Propellant Rocket Motors," Journal of Spacecraft and Rockets, Vol. 7, No. 5, May 1970, pp. 626-628.
3. "Solid Rocket Motor Igniters," NASA Space Vehicle Design Criteria (Chemical Propulsion) NASA SP-8051, National Aeronautics and Space Administration, March 1971, p. 61.